ABOVEGROUND BIOMASS PARTITIONING DUE TO THINNING IN NATURALLY REGENERATED EVEN-AGED SHORTLEAF PINE (*Pinus echinata* Mill.) STANDS IN SOUTHEAST OKLAHOMA

By

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CHAPTER I

INTRODUCTION

1.1. Shortleaf Pine

Shortleaf pine (*Pinus echinata* Mill.) is one of the four most important commercial conifers in southern United States (Burns and Honkala 1990). It is also locally known as southern yellow, oldfield, short straw or Arkansas soft pine. Shortleaf pine is most widely distributed among the all other southern pine in United States. It grows in 22 states comprising more than 1,139,600 km^2, from southeastern New York to eastern Texas (Willet 1986). The principal timber area of shortleaf pine is found in eastern Oklahoma and western Arkansas (Lynch et al. 2003). Shortleaf pine grows mainly in humid regions (Fowells 1965) and it tolerates a wide range of soil and site conditions, maintaining its growth rate for a relatively long period (Lawson and Kitchens 1983). Natural regeneration is a common method of regenerating shortleaf pine on much of the extensive forestland in private ownership throughout its range (Lawson 1978). Thinning is a typical midrotation management practice done in shortleaf pine stands.

Since the 1960's shortleaf pine has been declining due to the replacement of mature stands with other southern pines, mainly by loblolly pine (McWilliams et al. 1986). However, shortleaf pine is still heavily used for lumber, plywood and other structural materials and pulpwood. As many studies have been more focused on other southern pines, there is limited published information concerning growth and biomass estimation for shortleaf forest stands. Moreover, there are few studies of shortleaf biomass estimation that account for a range of stand densities and which provide estimates for the different tree biomass components to obtain a picture of biomass partitioning for these stands. Modern forest products technology can utilize not only the main stem (bole wood) but also in some cases may utilize the other tree components including branch wood and foliage. Therefore, it is necessary to develop equations that can accurately predict branch and foliage as well as stem and bark biomass for shortleaf pine forests.

1.2. Purpose of Study

This study examines the effect of thinning treatments on the partitioning of biomass among branches, foliage, bark and bole wood in shortleaf pine. First measurement and estimation of component biomass is presented. Then relationships between biomass components and branch and tree dimensions were established (Manuscript I). These biomass equations were then used to estimate the amount of biomass per tree component and per hectare to provide information which is utilized in a subsequent thinning response study (Manuscript II).

CHAPTER II

MANUSCRIPT I

DEVELOPING THE TREE COMPONENT BIOMASS EQUATIONS
FOR NATURALLY REGENERATED SHORTLEAF PINE
(*Pinus echinata* Mill.) IN SOUTHEAST OKLAHOMA

Abstract

Tree component (branch, foliage and tree bole) biomass equations were developed based on destructive measurement of 48 shortleaf pine (*Pinus echinata* Mill.) trees, ranging from 5 to 33 cm in dbh. Measurements were taken from a thinning study established in an even-aged, natural stand of shortleaf pine and consisting of 12 permanent plots established during 1988-1989. Thinning treatments included unthinned control plots and plots thinned to 70%, 50% and 30% full stocking. Equations for prediction of shortleaf pine branch-level biomass were fitted first by nonlinear regression based on ordinary least squares (OLS). Branch basal diameter, height of the branch and the ratio of total height to dbh were significant in predicting both branch wood and foliage biomass. Branch-level mixed-effect models were also developed by using random parameters at the tree level. The mixed-effect model was found to be more realistic representation of data than the model fitted by the OLS method because the mixed-effect method considers the correlations among the branch measurements within a tree. The developed branch-level equations were used to predict the biomass of branches that were not sampled on each biomass sample tree. The relationships were also developed at the individual tree-level to predict shortleaf pine biomass components using nonlinear seemingly unrelated regression methods (NSUR). Equations based on *DBH* were not substantially different than the equations based on other variables along with *DBH*. The equations developed can be used to estimate the aboveground tree or tree component biomass of shortleaf pine stands in the region from which the data were obtained.

2.1. Introduction

2.1.1. Biomass Modeling

Biomass equations help to quantify tree and stand biomass. Forest biomass estimation is used in practice to quantify fuel and wood stock and to allocate harvest amounts (Dias et al. 2006). Biomass assessment is important in national development planning as well as for scientific studies of ecosystem productivity, carbon budget, etc. (Parresol 1999, Zhang et at. 2004). The aboveground component biomass (bole wood, foliage and branches) estimation of forest stand is of interest to the researcher and/or manager for application on a variety of scales. At large scales, estimation of carbon storage in forests requires information of total tree biomass. At smaller scales, foresters working at stand level require mainly stem wood biomass to determine thinning intensity and harvest yield. Branch wood biomass can be important in pulpwood production if branches are chipped on site. For a scientific study of the balance and flow of nutrients one has to consider various tree components because the nutrient concentration differs with tissue type in different parts of tree. The estimation of foliage biomass is very important in this type of study.

With the increasing concerns relating to global warming, the importance of forests in assimilation of atmospheric CO_2 is being recognized. The study of amount of CO_2 stored in forest biomass has gained special attention since UN Framework Convention on Climate Change (UNFCC) and its Kyoto protocol (Myneni et al. 2001, Fang et al. 2001). The accurate estimation of forest biomass is prerequisite to an explanation of the role of forests in regional and global carbon cycles.

2.1.2. Tree Biomass Equation

Regression equations have often been used to relate tree biomass to various dendrometric tree variables. Among many existing regression models for tree biomass components, most of them have been developed utilizing one of the following three forms (Parresol 1999):

Linear (additive error): $$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ...+ \beta_j X_j + \varepsilon \quad (1)$$

Nonlinear (additive error): $$Y = \beta_0 X_1^{\beta_1} X_2^{\beta_2} ......X_j^{\beta_j} + \varepsilon \quad (2)$$

Nonlinear (multiplicative): $$Y = \beta_0 X_1^{\beta_1} X_2^{\beta_2} ......X_j^{\beta_j} \varepsilon \quad (3)$$

where,

Y is total tree or component biomass,

X_1 to X_j are tree dimension variables,

β_j's are model parameters, and

ε is a random error term.

The tree-level equations predict bole wood, whole tree biomass or biomass of certain components (e.g. foliage, branch, bole wood) as a function of diameter or diameter and height and sometimes other variables for the tree. Biomass equations, which include independent variables other than diameter and height, such as live crown length or diameter at base of the crown, have also been developed (Zhang et al. 2004, Clark 1982). Equation (1) can be solved by multiple linear regression techniques, while nonlinear equation (2) requires use of iterative procedures for parameter estimation. Using these two equations the problem of heteroscedasticity can be solved by weighted analysis (Kutner et al. 2004). Forest biomass models are usually influenced by heteroscedasticity in the data (Berhe 2005). Equation (3) is solved by taking logarithms on both sides and applying linear regression techniques. This transformation also solves the problem of heteroscedasticity. One of the most commonly used equations for tree biomass components is model (3) (Fehrmann and Kleinn 2006, Green et al. 2005, Ter-Mikaelian and Korsukhin 1997, Zianis et al. 2005, Sabatia 2007).

Although the shortleaf pine is important in terms of area and growing stock, very few studies have been done relating to its biomass modeling. Clark III and Taras (1976), Shifley (1987), and Loomis et al. (1966) are a few of the previous studies concerning shortleaf biomass. A more recent study was Sabatia (2007). He has developed models that predict the component biomass of individual tree for even-aged stands in eastern Oklahoma. However, Sabatia's (2007) data were restricted to a relatively better quality site for the eastern Oklahoma region. The current study utilizes data from a poorer quality site.

2.1.3. Problem Statement

A large number of biomass models, having different forms and various predictor variables, exist in literature; and it is always an issue which model form best fits a particular data set. Using more variables requires measurement of a large number of trees to cover the full range of the variables while using few variables in a model can reduce unnecessary felling of trees (de Gier 2003). The excessive addition of variables, although they may be statistically significant, does not usually lead to a substantial increase in R^2 or decrease in SSE (Sum of Squared Errors) (Ter-Mikaelian and Korsukhin 1997). In addition, lack of clarity in the description of existing biomass models regarding the range of *DBH*, cover type, geographical location and management system for which they are applicable makes the use and estimation of some biomass models uncertain. Biomass equations also vary from forest type, age, site condition and stand density and climate (Fang et al. 2001, Zianis et al. 2005, Sabatia 2007). Therefore, it is always good practice to develop the local equations when possible. For forest management purposes, simple models with few predictor variables are usually preferred.

2.1.4. Objectives

The objectives of this study were to fit biomass component equations at branch-level and to the tree-level and select the best models based on fit index (FI), RMSE (Root Mean Square Error), AIC (Akaike Information Criteria) and constancy of variance.

2.2. Methods and Materials

2.2.1. Study Area

The study was conducted in natural shortleaf pine stands in northwestern Pushmataha County, Ouachita Mountain, Oklahoma. Data were collected from plots established during 1988-1989 on industrial forest land currently owned by Plum Creek Timber Company. According to the USDA-SCS soil survey, the study area falls in the Carnasaw (Fine, mixed, semiactive, thermic Typic Hapludults) –Pirum(Fine-loamy, siliceous, semiactive, thermic Typic Hapludutls)-Clebit (Loamy-skeletal, siliceous, semiactive, thermic Lithic Dystrudepts) soil association (Bain and Watterson 1979, cited in Wittwer et al. 1996). The soils are classified as well drained and deep, moderately deep and shallow soil. Average annual precipitation, recorded for the county is 50.43 in. (Oklahoma Climatological Survey 2008). The site index at base age 50 was 17.4 m (Wittwer et al., 1998). According to Wittwer et al. (1996), the vegetation in the area was predominantly shortleaf pine stands about 25-30 years old in 1989. The stand conditions at the time of biomass data collection are given in Table 1.

2.2.2. Data collection

2.2.2.1. Plot measurement

Twelve square treatment plots 0.16 ha in size were distributed among three blocks. Within each of these treatment plots a 0.04 ha measurement plot was established. Each measurement plot was surrounded by 10 m wide isolation strip. *DBH*, crown height (*CH*), crown width (*CW*), and total tree height (*HT*) of each tree in the plots were recorded every year since the establishment of the plots. The inventory measurement data from 2006 were utilized for this study.

Table 1. Average stand characteristics by treatment in 2006.

Treatment	Stocking[1]	Trees/ha	Quadratic mean DBH (cm)	Basal Area m^2/ha
30 FS	79.7	565	25.9	28.2
50 FS	102.5	860	22.8	35.2
70 FS	126.7	1202	21.3	42.5
CONTROL	144.8	1987	16.9	44.2

[1]Stocking level expressed as a percentage of full stocking level.

2.2.2.2. Sample trees

Forty eight (48) sample trees, representing the existing diameter range (5-33 cm), were felled and measured during January and February of 2007. Trees were felled at about 0.14 meter above the ground. Data from the inventory of plots in 2006 (which represent conditions after the 2005 growing season) were used to select the sample trees. Sample trees were selected from both thinned and unthinned plots to represent as wide a range as possible of diameters. Within each diameter class, trees were randomly selected in each plot. Thinning treatments included were thinned in 1989 using the stocking guide of Roger (1983) to 70% (70 FS), 50% (50 FS), 30% (30 FS) full stocking and unthinned control plots (CONTROL) with >170 % of full stocking.

2.2.2.3. Sub-sampling

After tree felling, the diameter of each living branch was measured at base next to the bole by electronic calipers to the nearest 0.01 cm. A randomly selected branch per whorl and the terminal branch were chosen for more detailed biomass measurements (472 branches). Before any branches were cut from the tree, total height of the tree (*HT*), height to the live crown (*CHT*), and height to each branch (*h*) were measured and recorded. All branches were then cut from the bole and only the sample branches were retained for further measurement. The foliage was collected and placed in paper sack separately for each sample branch. Each sample branch was then cut into lengths of about 10-30 cm and packed in paper or jute sack. Each branch and foliage sample was oven-dried at 60^0 C as long as required to reach its stable dry weight and this weight was recorded.

2.2.2.4. Estimating bole wood and bark dry weight

Once the branches were removed, the bole was measured, sectioned and weighed (green weight). Bucking points were marked at 1.37m (point of breast height measurement) and every 2.13 m interval thereafter up to the point of 1cm bolt top diameter. Bucking stopped at any point greater than 1cm top diameter if the last section was less than 2.13m long. This remaining top part of bole was considered as the terminal branch. Some variability in a few bucking points was necessary to allow for irregularities due to bole taper or branches. A sample of green wood consisting of a disc about 3cm thick (*cookies*) was cut off the upper end of each bolt and the stump. Both inside and outside bark diameters for each disc were measured and recorded using calipers and each cookie was labeled and placed in a plastic bag. These bags were then kept in a cold storage until the laboratory analyses.

In laboratory, the green weight of disc with and without the bark and a green bark sample were measured. Discs without bark and sample bark from each disc were dried in an oven at 60^0C until the weight was stable. Using the ratio of dry sample bark weight to green sample bark weight, dry weight of bark for each disk was determined. Dry weight-green weight ratios were calculated for each disc with and without bark. These ratios were utilized in following equation to determine the dry weight of the wood and bark on each bolt.

$$DW_{wb} = GW \times \frac{\left(\frac{dw_1}{gw_1}\right) \times d_{1ob}^2 + \left(\frac{dw_2}{gw_2}\right) \times d_{2ob}^2}{d_{1ob}^2 + d_{2ob}^2} \tag{4}$$

where,

DW_{wb} is dry weight of bolt with bark (kg),

GW is green weight of bolt with bark (kg),

dw_1 is dry weight of disc with bark at the lower end of bolt,

gw_1 is green weight of disc with bark at the lower end of bolt,

d_{1ob} is geometric mean diameter, outside bark, of disc at lower end of bolt,

dw_2 is dry weight of disc with bark at the upper end of bolt,

gw_2 is green weight of disc with bark at the upper end of bolt, and

d_{2ob} is geometric mean diameter, outside bark, of disc at upper end of bolt.

Equation (4) gives the weighted average density using the discs at the top and bottom of each bole section. Disc dry weight-green weights ratio varied from 0.4 to 0.7, which is similar to results found by Sabatia (2007). To calculate the dry weight of bolts without bark, the same equation was used, replacing outside bark diameter by inside bark diameter for each disc and using disc dry weight without bark instead of disc dry weight with bark. Tree bole wood and total bole (including bark) biomass were computed by summing up the dry wood weights of bolts without and with bark, respectively. The bark biomass for a tree is then computed by subtracting bole wood from total bole biomass of a tree. The bole wood, total bole and bark biomass estimates for each tree are given in Appendix I.

2.2.3. Statistical Analysis for Parameter Estimation

Various regression models were fitted to the biomass data set using SAS/STAT software®, Version 9.1.3 (SAS Institute Inc. 2002-2004). For crown biomass (branch wood and foliage), model fitting was done at branch-level first and then applied to estimate the tree-level branch wood and foliage biomass. Then relationships between biomass components and tree dimensional variables were established at the tree-level. Finally, these tree-level biomass estimation equations were applied to estimate stand biomass (plot-level) for each plot in the shortleaf pine thinning study described above.

2.2.3.1. Estimation of Branch and Foliage Biomass

2.2.3.1.1. Branch-Level Estimation

Because it was not feasible to weigh every single branch in the shortleaf pine sample trees, regression equations were developed to estimate biomass for branches that were not sampled. Using sample branch measurement data, regression equations were fitted based on the model used by Ek (1979).

$$w = \beta_0 d^{\beta_1} R^{\beta_2} S^{\beta_3} \varepsilon \qquad (5)$$

where,

w is the branch wood or branch foliage dry weight in kilograms and hectograms, respectively,

d is branch basal diameter in centimeters,

R is measure of depth of branch in crown, in meters, which can be computed as (*HT*-*h*), where h is height to the branch and HT is the total height of the tree,

S is the ratio (*HT*/*DBH*) where DBH is diameter of the tree at breast height (1.37m),

$\beta_0, \beta_1, \beta_2$ and β_3 are parameters, and

ε is the error term.

Equation (5) was converted to a linear form by logarithmic transformation and STEPWISE SELECTION, using REG procedure in SAS/STAT software®, Version 9.1.3, was performed to select the significant predictor variables (significant if $p \leq 0.15$). The effect of stand density was also investigated by introducing dummy variables before executing the stepwise selection. The dummy variables were assigned as follows;

X_1 = 1 for thinning to 30% full stocking (30 FS), otherwise 0

X_2 = 1 for thinning to 50% full stocking (50 FS), otherwise 0

X_3 = 1 for thinning to 70% full stocking (70 FS), otherwise 0

If a measurement comes from an Unthinned (CONTROL) plot, all X_i will have the value of zero.

The log transformed model with dummy variables is:

$$\ln(w) = \beta_0 + \beta_1 \ln(d) + \beta_2 \ln(R) + \beta_3 \ln(S) + \beta_4 X_1 \ln(d) + \beta_5 X_1 \ln(R) + \beta_6 X_1 \ln(S) + \beta_7 X_2 \ln(d) + \beta_8 X_2 \ln(R) + \beta_9 X_2 \ln(S) + \beta_{10} X_3 \ln(d) + \beta_{11} X_3 \ln(R) + \beta_{12} X_3 \ln(S) \quad (6)$$

where ln is the natural logarithm.

Equations (7) and (8), which retain only variables selected from stepwise selection and transformed back to nonlinear form, were fitted by two different methods. First, the equations (7) and (8) were fitted using the ordinary least-squares (OSL) method for branch wood and foliage biomass data, respectively. These fittings were considered Model I type equations. The significance of dummy variables modifies the relationship for different thinning levels.

Model I:

$$w_{branch\ wood} = e^{\beta_0} d^{\beta_1 + \beta_4 X_1} R^{\beta_2 + \beta_5 X_1} S^{\beta_3 + \beta_6 X_2} \quad (7)$$

$$w_{foliage} = e^{\beta_0} d^{\beta_1} R^{\beta_8 X_2 + \beta_{11} X_3} S^{\beta_3} \quad (8)$$

Equations in Model I were then modified to obtain a mixed-effects model including random tree-level effects. Mixed-effects models can account for correlation due to grouping in data structure that commonly occurs in forestry applications (Gregoire et al. 1995, Biging 1985, Budhathoki et al. 2008). Lynch et al. (2005) found that parameter estimates have been improved by using mixed-effects models for the height-diameter relationship in Cherrybark oak.

When we introduce random tree-level parameters equations (7) and (8) become;

Model II:

$$w_{branch\ wood} = e^{(\beta_0+u)} d^{\beta_1+\beta_4 X_1} R^{\beta_2+\beta_5 X_1} S^{\beta_3+\beta_6 X_2} \tag{9}$$

$$w_{foliage} = e^{(\beta_0+u)} d^{\beta_1} R^{\beta_8 X_2+\beta_{11} X_3} S^{\beta_3} \tag{10}$$

where, u is random effect associated with fixed-effects parameter $\beta_{0.}$

Models I and II were fitted using SAS PROC NLIN and PROC NLMIXED respectively for branch wood and foliage biomass data. Both equations were weighted as a function of *d,* to address the heterogeneous variance properties of the datasets (Parresol 2001). The weight functions $d^{-3.5}$ and d^{-3} were used for the branch wood biomass equation and foliage equation, respectively.

The best models were selected based on Fit Index (FI), Root Mean Square Error (RMSE) and Akaike information criteria (AIC) (Akaike 1974). These selected equation were then used to estimate the biomass for those branches that were not sampled.

2.2.3.1.2. Tree-Level Estimation

The tree-level branch wood and foliage biomass were computed by summing up the estimated branch biomass for each of the branches in a tree. However, actual dry weights were used for those branches that were sampled.

2.2.3.2. Fitting Tree-Level Biomass Equations

Using data given in Appendix I, equation (3) was fitted to predict shortleaf pine biomass components at the individual tree level using nonlinear seemingly unrelated regression methods (NSUR). The PROC NLIN and PROC MODEL procedures in SAS/STAT® software, Version 9.1.3 (SAS Institute Inc. 2002-2004) were used to execute this parameter estimation. Prior to final estimation, equation (3) was converted to a linear form by logarithmic transformation and STEPWISE SELECTION, using REG procedure in SAS software (Version 9.1.3), was performed to select the significant predictor variables for each biomass component. The effect of stand density was also investigated by introducing dummy variables before executing the stepwise selection. The dummy variables were assigned as follows;

X_1 = 1 if the stand was under CONTROL treatment, otherwise 0

X_2 = 1 for thinning to 70% full stocking, otherwise 0

X_3 = 1 for thinning to 50% full stocking, otherwise 0

Three preliminary log transformed forms of equation (3) - with all possible interaction with dummy variables, were proposed for stepwise selection.

$$\ln(Y) = \beta_0 + \beta_1 \ln(DBH) + \beta_2 X_1 + \beta_3 X_2 + \beta_4 X_3 + \beta_5 X_1\ln(DBH) + \beta_6 X_2\ln(DBH) + \beta_7 X_3\ln(DBH) \qquad (11)$$

$$\ln(Y) = \beta_0 + \beta_1 \ln(DBH) + \beta_2 \ln(HT) + \beta_3 X_1 + \beta_4 X_2 + \beta_5 X3 + \beta_6 X_1\ln(DBH) + \beta_7 X_2\ln(DBH) + \beta_8 X_3\ln(DBH) + \beta_9 X_1\ln(HT) + \beta_{10} X_2\ln(HT) + \beta_{11} X_3\ln(HT) \qquad (12)$$

$$\ln(Y) = \beta_0 + \beta_1 \ln(DBH) + \beta_2 \ln(HT) + \beta_3 \ln(CW) + \beta_4 \ln(CL) + \beta_5 X_1 + \beta_6 X_2 + \beta_7 X_3 + \beta_8 X_1\ln(DBH) + \beta_9 X_2\ln(DBH) + \beta_{10} X_3\ln(DBH) + \beta_{11} X_1\ln(HT) + \beta_{12} X_2\ln(HT) + \beta_{13} X_3\ln(HT) + \beta_{14} X_1\ln(CW) + \beta_{15} X_2\ln(CW) + \beta_{16} X_3\ln(CW) + \beta_{17} X_1\ln(CL) + \beta_{18} X_2\ln(CL) + \beta_{19} X_3\ln(CL) \qquad (13)$$

where,

ln is the natural logarithm,

Y is the tree or tree component biomass (kg),

DBH is diameter at breast height (cm),

HT is the total height of the tree (m),

CW is crown width (m),

CL live crown length (m),

X_1, X_2, and X_3 are dummy variables, and

β_0 to β_{19} are parameters.

The significant variables in Equation (11) (12) and (13) were evaluated with STEPWISE selection using REG procedure in SAS/STAT software® , Version 9.1.3. Predictor variables are considered significant if p≤0.15.

Equation (11) with only the DBH variable was used to select the significant dummy variables and their interactions for the bole wood, total bole (bole wood + bark biomass), branches and foliage biomass equations.

$$Y_{BOLEWOOD/TOTALBOLE} = e^{(\beta_0+\beta_2 X_1)} DBH^{(\beta_1+\beta_5 X_1)} \tag{14}$$

$$Y_{BRANCH} = e^{(\beta_0+\beta_3 X_2+\beta_4 X_3)} DBH^{(\beta_1+\beta_5 X_1)} \tag{15}$$

$$Y_{FOLIAGE} = e^{(\beta_0+\beta_3 X_2+\beta_4 X_3)} DBH^{(\beta_1)} \tag{16}$$

Equation (14) is a converted nonlinear form of equation (11) with only selected predictor variables for both bole wood and total bole biomass equations. Similarly, equations (15) and (16) are also the converted nonlinear forms of equation (11) for branch and foliage biomass, respectively. Scatter plots of residuals revealed heteroscedasticity, mainly with respect to DBH for all biomass equations. Therefore, appropriate weights were determined by re-fitting the equation with weights which were functions of *DBH*. The weight functions used were DBH^{-2} for bole wood, total bole and total tree, $DBH^{-2.5}$ for branch and DBH^{-1} for foliage.

The parameters in equations (14) (15) and (16) were then fitted in system of equations (17) with the procedure PROC MODEL in SAS/STAT®, Version 9.1.3 (SAS Institute Inc. 2002-2004), using weighted nonlinear seemingly unrelated regressions (NSUR) (Gallant 1987).

$$
\begin{aligned}
&Y_{BOLEWOOD} = e^{(\beta_{10}+\beta_{12}X_1)} DBH^{(\beta_{11}+\beta_{15}X_1)} \\
&Y_{TOTALBOLE} = e^{(\beta_{20}+\beta_{22}X_1)} DBH^{(\beta_{21}+\beta_{25}X_1)} \\
&Y_{BRANCH} = e^{(\beta_{30}+\beta_{33}X_2+\beta_{34}X_3)} DBH^{(\beta_{31}+\beta_{35}X_1)} \\
&Y_{FOLIAGE} = e^{(\beta_{40}+\beta_{43}X_2+\beta_{44}X_3)} DBH^{(\beta_{41})} \\
&Y_{TOTALTREE} = e^{(\beta_{20}+\beta_{22}X_1)} DBH^{(\beta_{21}+\beta_{25}X_1)} + e^{(\beta_{30}+\beta_{33}X_2+\beta_{34}X_3)} DBH^{(\beta_{31}+\beta_{35}X_1)} \\
&+ e^{(\beta_{40}+\beta_{43}X_2+\beta_{44}X_3)} DBH^{(\beta_{41})}
\end{aligned}
\tag{17}
$$

where,

Left-hand-side dependent variables in the equations are the tree biomass components in kilograms, β_{ij} are parameters, and X_1, X_2 and X_3 are dummy variables.

Similarly, the stepwise regression procedure in equations (12) and (13) with variables *HT*, *CW* and *CL* in addition to *DBH*, obtained following best biomass equation for bole wood, total bole, branch and foliage. Again, the appropriate weight function for each equation was determined by re-fitting the equation with different weight functions of *DBH*.

The *DBH*, *HT*, and/or *CW* equations are:

$$Y_{BOLEWOOD} = e^{(\beta_0)} DBH^{(\beta_1)} HT^{(\beta_2+\beta_9 X_1)} \tag{18}$$
$$Y_{TOTALBOLE} = e^{(\beta_0+\beta_3 X_1)} DBH^{(\beta_1)} HT^{(\beta_2)} \tag{19}$$
$$Y_{BRANCH} = e^{(\beta_0)} DBH^{(\beta_1+\beta_{10} X_3)} CW^{(\beta_3)} \tag{20}$$
$$Y_{FOLIAGE} = e^{(\beta_0+\beta_6 X_2+\beta_7 X_3)} DBH^{(\beta_1)} CW^{(\beta_3)} \tag{21}$$

These selected equations were then fitted in system of equations (22) using weighted nonlinear seemingly unrelated regressions (NSUR) methods as described above. The weight function used were $DBH^{-2.5}$ for bole wood and total bole, DBH^{-2} for total tree, DBH^{-3} for branch and DBH^{-2} for foliage.

$$\begin{aligned}
&Y_{BOLEWOOD} = e^{(\beta_{10})} DBH^{(\beta_{11})} HT^{(\beta_{12}+\beta_{19} X_1)} \\
&Y_{TOTALBOLE} = e^{(\beta_{20}+\beta_{23} X_1)} DBH^{(\beta_{21})} HT^{(\beta_{22})} \\
&Y_{BRANCH} = e^{(\beta_{30})} DBH^{(\beta_{31}+\beta_{310} X_3)} CW^{(\beta_{33})} \\
&Y_{FOLIAGE} = e^{(\beta_{40}+\beta_{46} X_2+\beta_{47} X_3)} DBH^{(\beta_{41})} CW^{(\beta_{43})} \\
&Y_{TOTALTREE} = e^{(\beta_{20}+\beta_{23} X_1)} DBH^{(\beta_{21})} HT^{(\beta_{22})} + e^{(\beta_{30})} DBH^{(\beta_{31}+\beta_{310} X_3)} CW^{(\beta_{33})} \\
&+ e^{(\beta_{40}+\beta_{46} X_2+\beta_{47} X_3)} DBH^{(\beta_{41})} CW^{(\beta_{43})}
\end{aligned} \tag{22}$$

where,

Left-hand-side dependent variables in the equations are the tree biomass components in kilograms, β_{ij} are parameters, and X_1, X_2 and X_3 are dummy variables.

For tree component regression equations, we expect that the predictions for the biomass components should sum to the prediction for the total tree biomass. As proposed by Parresol (1999, 2001), this additivity can be guaranteed using nonlinear seemingly unrelated regression or NSUR. In this method a set of nonlinear regressions was specified in such way that (i) total tree biomass equation is restricted to have same independent variables and coefficients as the component equations and (ii) each regression equation can utilize its own unique weight function. This technique considers the contemporaneous correlations among the regression residuals for the system of equations and gives more efficient parameters estimates than would be obtained by using OLS to estimate parameters in each equation separately.

2.3. Results and Discussion

2.3.1. Branch-level Biomass Estimation

Parameter estimates, standard errors, and confidence intervals from fitting Model I (equations (7) and (8)) and Model II (equations (9) and (10)) are presented in Tables 2 and 3, respectively. All parameters estimated in Tables 2 and 3 below were significant at 95% confidence level.

Table 2a. Parameter estimates from SAS PROC NLIN for the Model I branch wood biomass equation.

Parameter	Estimate	Standard Error	95% Confidence Interval
β_0	-4.1508	0.0357	(-4.2209,-4.0807)
β_1	2.2644	0.0487	(2.5484,2.7400)
β_2	0.2099	0.0374	(0.1363,0.2834)
β_3	-0.2734	0.0592	(-0.3897,-0.1571)
β_4	-0.1793	0.0642	(-0.3054,-0.0532)
β_5	0.2384	0.0644	(0.1120,0.3649)
β_6	0.4439	0.0996	(0.2481,0.6397)

Table 2b. Parameter estimates from SAS PROC NLIN for the Model I branch foliage biomass equation.

Parameter	Estimate	Standard Error	95% Confidence Interval
β_0	-1.5876	0.0381	(-1.6625,-1.5127)
β_1	1.6823	0.0411	(1.6016,1.7630)
β_3	-0.4457	0.1017	(-0.6456,-0.2458)
β_8	-0.1510	0.0483	(-0.2459,-0.0561)
β_{11}	-0.1092	0.0437	(-0.1950,-0.0234)

Since dummy variables X_1 and X_2 were significant in the branch wood equation, the 70 FS and Unthinned plots had similar relationships. This implies that there is no effect of stand density between these two treatment levels on the branch wood equation. However, dummy variables X_2 and X_3 were found to be significant in foliage biomass indicating that foliage biomass relationships are similar in the highly thinned (30 FS) and the Unthinned stands. In the cases where dummy variables where not significant the variable *S* may have acted as a measure of stand density.

All independent variables in equation (7), i.e., basal branch diameter (*d*), depth of branch in crown (*R*) and ratio of *HT*/*DBH* (*S*) were found to be significant for branch biomass under all stand densities. Similar results were also found for the foliage biomass equation (8) with the exception that *R* was not significant in case of unthinned and 30 FS stand density. The depth of branch in a tree from unthinned and highly thinned stands did not influence the biomass of foliage. For branch wood, β_1 (basal branch diameter, *d*) and β_2 (depth of branch in crown, *R*) were positively significant. This implies that as either of these attributes increase- provided other variables constant, the branch biomass also increases. For the foliage biomass equation basal branch diameter *d* had the same positive relationship, while β_2 (depth of branch in crown, *R*) was negative for those stand densities where the variable was significant. Unlike wood biomass, those branches deeper in the crown had less foliage biomass. Sabatia (2007) found similar effects of *R* in branch foliage biomass. Ek (1979) has also mentioned that *R* was highly significant in estimating the leaf weight in *populus tritis*.

Table 3a. Parameter estimates from SAS PROC NLMIXED for the Model II branch wood biomass equation.

Parameter	Estimate	Standard Error	95% Confidence Interval
β_0	-4.1599	0.03629	(-4.233,-4.0868)
β_1	2.6615	0.0468	(2.5672,2.7558)
β_2	0.2014	0.03466	(0.1315,0.2712)
β_3	-0.2512	0.07598	(-0.4042,-0.09814)
β_4	-0.2049	0.06969	(-0.3452,-0.06453)
β_5	0.2655	0.0662	(0.1322,0.3989)
β_6	0.3768	0.1433	(0.08811,0.6655)
σ_u^2	0.0056	0.00245	(0.000707,0.01058)

Table 3b. Parameter estimates from SAS PROC NLMIXED for the Model II foliage biomass equation.

Parameter	Estimate	Standard Error	95% Confidence Interval
$\beta 0$	-1.60000	0.04376	(-1.6881,-1.5119)
$\beta 1$	1.66790	0.03868	(1.5900,1.7458)
$\beta 3$	-0.51830	0.1267	(-0.7725,-0.2631)
$\beta 8$	-0.14590	0.04402	(-0.2345,-0.05725)
$\beta 11$	-0.09735	0.04114	(-0.1802,-0.01448)
σ_u^2	0.01803	0.009045	(-0.00019,0.03625)

Estimates of the variance of the random parameter u in Model II were significant for branch wood biomass (P value = 0.026, α=0.05) and marginally insignificant for branch foliage (P value = 0.0523) at α= 0.05. This significance level α is arbitrary, so that if we consider α = 0.1, the random parameter would be significant in both cases.

2.3.1.1. Model Comparison

Fit statistics calculated for individual treatments level using the parameters estimated above were given in the table below. Fit Index (FI, proportion of total variation explained) and Root Mean Square Error (RMSE) for Model I and Model II for branch wood and foliage equations are presented in Table 4 and 5, respectively.

Table 4. Fit Index, RMSE and Akaike Information criterion (AIC) in Model I (OLS) and Model II (mixed-effect) for the branch wood biomass equation.

		Model I(OLS) (AIC = -358.07)		Model II(Mixed) (AIC = -2821)	
Treatment	**Equation**	**FI**	**RMSE**	**FI**	**RMSE**
30FS	$Y = e^{\beta_0} d^{\beta_1+\beta_4 X_1} R^{\beta_2+\beta_5 X_1} S^{\beta_3}$	0.9728	0.2138	0.9725	0.2149
50FS	$Y = e^{\beta_0} d^{\beta_1} R^{\beta_2} S^{\beta_3+\beta_6 X_2}$	0.9561	0.1224	0.9547	0.1242
70FS	$Y = e^{\beta_0} d^{\beta_1} R^{\beta_2} S^{\beta_3}$	0.9567	0.1882	0.9564	0.1888
CTRL	$Y = e^{\beta_0} d^{\beta_1} R^{\beta_2} S^{\beta_3}$	0.9743	0.1212	0.9741	0.1217

$Fit\ \ Index\ \ (FI) = 1 - \left(\sum \left(Y_i - \hat{Y}_i\right)^2\right) / \left(\sum \left(Y_i - \overline{Y}_i\right)^2\right)$; $RMSE = \sqrt{\left(\sum \left(Y_i - \hat{Y}_i\right)^2 / (n - p)\right)}$

Table 5. Fit Index, RMSE and Akaike Information criterion (AIC) in Model I (OSL) and Model II (mixed-effect) for the foliage biomass equation.

		Model I(OLS) (AIC = 1206.15)		Model II(Mixed) (AIC = -646.7)	
Treatment	**Equation**	**FI**	**RMSE**	**FI**	**RMSE**
30FS	$Y = e^{\beta_0} d^{\beta_1} S^{\beta_3}$	0.5167	1.0662	0.5269	1.0549
50FS	$Y = e^{\beta_0} d^{\beta_1} R^{\beta_8 X_2} S^{\beta_3}$	0.4821	0.6691	0.4829	0.6686
70FS	$Y = e^{\beta_0} d^{\beta_1} R^{\beta_{11} X_3} S^{\beta_3}$	0.3013	0.9315	0.2745	0.9491
CTRL	$Y = e^{\beta_0} d^{\beta_1} S^{\beta_3}$	0.5891	0.8461	0.5967	0.8383

FI and RMSE didn’t differ much between Model I and Model II. For foliage biomass equation Model II has slightly better Fit Index and smaller RMSE, except for the 70 FS stand density. Model II has smaller AIC value for both branch wood and foliage biomass. Importantly, Model II better represents the data structure than Model I because the random effect involved accounts for the fact that branches are selected in a cluster within a tree and not individually at random as assumed by least square estimation in Model I. Since Model II had a smaller AIC value than Model I and the variance component associated with tree random effect is statistically significant, Model II, the mixed-effects model, is considered to be more reliable in prediction of both branch wood and foliage biomass. Therefore, Model II is better in prediction of individual branch biomass. Although the random effect variance for the foliage model was not significant at the 0.05 level, Model II had a much lower AIC for foliage than Model I. Therefore, Model II was used to estimate the branch and foliage biomass in this study.

Residual plots for these equations (Model II) are presented in Appendix II. Both plots suggest no violation of the constant error variance assumption. However, foliage biomass predictions may have some bias for bigger branches. The plots indicate that foliage weights have been somewhat under estimated when they are large.

2.3.2. Tree-Level Biomass Estimation

Parameter estimates, standard errors and test information for the system of additive biomass equations (17) with *DBH* as only dendrometric independent variables are presented in Table 6. All the parameters in the table are found to be significant at α= 0.05. Statistically significant dummy variables and their interactions with *DBH* indicate that stand density has an effect on estimation of component biomass.

Table 6. Parameter estimates, standard errors and test information of *DBH* based biomass equations fitted in the system of equations (17).

Parameter	Estimate	Standard Error	t value	*P* value
β_{10}	-1.71762	0.1267	-13.56	<.0001
β_{12}	-0.80744	0.2388	-3.38	.0015
β_{11}	2.170149	0.0395	54.90	<.0001
β_{15}	0.240777	0.0759	3.17	.0027
β_{20}	-1.54463	0.1073	-14.39	<.0001
β_{22}	-0.74323	0.1979	-3.76	.0005
β_{21}	2.153146	0.0334	64.37	<.0001
β_{25}	0.221604	0.0628	3.53	.0010
β_{30}	-7.85247	0.5477	-14.34	<.0001
β_{33}	-0.26449	0.0517	-5.12	<.0001
β_{34}	-0.40202	0.0846	-4.75	<.0001
β_{31}	3.538111	0.1625	21.77	<.0001
β_{35}	-0.04611	0.0132	-3.50	.0011
β_{40}	-6.27523	0.3834	-16.37	<.0001
β_{43}	-0.27104	0.0476	-5.70	<.0001
β_{44}	-0.36339	0.0667	-5.45	<.0001
β_{41}	2.577831	0.1156	22.30	<.0001

The coefficient of *DBH* was always positive for all component equations, which clearly indicates an increase in component biomass with increase in *DBH*.

The parameter estimates, their standard errors and test information for the system of biomass component equations (22) based on *DBH*, *HT* and/or crown width (*CW*) are presented in Table 7. Similar results for the coefficient of *DBH* were found for system of equations (22) as were indicated for the system of equations (17) above. *DBH* was positively related to all component biomass with the presence of other variables- *HT* and *CW*. The height variable did not enter all equations. *HT* had no statistically significant influence on crown biomass (branch wood and foliage).The positive sign of the *HT* coefficient in the bole wood and total bole equations implies that for the same *DBH*, taller trees contain more biomass. Crown width (*CW*) was entered with positive power in crown biomass equations. Along with the dummy variables, the significance of *CW* can be interpreted as a representation of the effects of different stand densities. Research has previously found that thinning tends to increase crown width (Peterson et al. 1997).

Table 7. Parameter estimates, standard errors and test information of *DBH*, *HT* and/or *CW* based biomass equations fitted in the system of equations (22).

Parameter	Estimate	Standard Error	t value	*P* value
β_{10}	-3.91542	0.2659	-14.72	<.0001
β_{11}	1.95453	0.0435	44.94	<.0001
β_{12}	1.01546	0.1254	8.1	<.0001
β_{19}	-0.03696	0.00856	-4.32	<.0001
β_{20}	-3.44778	0.2169	-15.89	<.0001
β_{23}	-0.09825	0.0211	-4.66	<.0001
β_{21}	1.96841	0.0368	53.56	<.0001
β_{22}	0.87753	0.1034	8.48	<.0001
β_{30}	-6.16769	0.8168	-7.55	<.0001
β_{31}	2.59124	0.3122	8.3	<.0001
β_{310}	-0.08006	0.0317	-2.53	.0152
β_{33}	0.73434	0.1982	3.71	.0006
β_{40}	-5.33157	0.5241	-10.17	<.0001
β_{46}	-0.13788	0.0302	-4.56	<.0001
β_{47}	-0.29838	0.0694	-4.3	<.0001
β_{41}	2.08693	0.2103	9.92	<.0001
β_{43}	0.35026	0.1316	2.66	.0109

Parameter estimates in Table 6 and 7 obtained by using NSUR to fit these systems of additive equations had lower standard errors than were obtained by the common approach of separately fitting the total tree and component biomass equations using OLS (ordinary least squares) (results for OLS not shown here). According to Parresol (1999, 2001), NSUR uses information from cross-equation correlations in the system of equations to reduce standard errors of parameter estimates compared to OLS. This method also eliminates logical inconsistency between the sum of predicted values for the tree components and the prediction for the total tree that can occur when these equations are fitted independently using OLS (Kozak 1970).

Statistics of fit for the equations (17); based on only *DBH* and fit statistic for the equations (22); based on *DBH*, *HT* and/or *CW* are given in the Table 8 and 9, respectively. The high fit index values for both equations show that the equations provide a good fit to the data. However, the fit index values were lower for branch wood and foliage equations compared to stem wood equations. This implies that the crown equations were associated with higher prediction error than stem wood equations. This fact is also supported by the studies conducted by Sabatia (2007) and Lambert et al. (2005). Some additional observations that can be made by examining these fit statistics include: *DBH* is essential in predicting both stem and crown biomass components; introducing *HT* variables slightly improved the fit index for stem equations but *HT* was not significant in predicting crown biomass components; and adding crown width (*CW*) didn't improve the fit statistic for foliage and branch biomass equations. It seems that dummy variables better explained the variation in branch wood biomass due to stand density than crown width in this study. Some studies suggested that adding crown length (*CL*) improved the crown component equation prediction (Pulkkinen 1991, Zhang et al. 2004). *CL* predictor was not found to be statistically significant in predicting branch wood and foliage biomass in present study. Moreover, these crown variables, crown width and crown length, are not always available because it is relatively difficult to measure them accurately in forest conditions. Residual plots for both systems of equations are given in Appendix III. All plots suggest no violation of the constant error variance assumption.

2.3.2.1. Comparison of two equations

Akaike's Information Criterion (AIC=444.17) calculated for the total tree equation from *DBH-HT* and/or *CW* based equations is not much smaller than AIC (=449.94) calculated from the *DBH*-based equation. This indicates that *DBH*-based equations are equally good in predicting biomass as the equations with additional variables for the data in this study.

Table 8. Fit Index and Root Mean Square Error for equations (17) utilizing only *DBH*.

Tree Component	Equation	Fit Index	RMSE
Bole Wood	$Y = e^{(\beta_{10}+\beta_{12}X_1)}DBH^{(\beta_{11}+\beta_{15}X_1)}$	0.9726	16.0790
Total Bole	$Y = e^{(\beta_{20}+\beta_{22}X_1)}DBH^{(\beta_{21}+\beta_{25}X_1)}$	0.9785	15.9323
Branch	$Y = e^{(\beta_{30}+\beta_{33}X_2+\beta_{34}X_3)}DBH^{(\beta_{31}+\beta_{35}X_1)}$	0.9238	6.3342
Foliage	$Y = e^{(\beta_{40}+\beta_{43}X_2+\beta_{44}X_3)}DBH^{(\beta_{41})}$	0.9356	1.0076
Total Tree	$Y = e^{(\beta_{20}+\beta_{22}X_1)}DBH^{(\beta_{21}+\beta_{25}X_1)} + e^{(\beta_{30}+\beta_{33}X_2+\beta_{34}X_3)}DBH^{(\beta_{31}+\beta_{35}X_1)} + e^{(\beta_{40}+\beta_{43}X_2+\beta_{44}X_3)}DBH^{(\beta_{41})}$	0.9755	23.4539

The system of equations (17) provides good balance between accurate prediction and use of easily-measured independent variables by utilizing only *DBH*, perhaps the most commonly and easily measured variable in forestry. Use of this *DBH*-based equation is suggested when tree height and other crown measurements are not available. Additional variables do not necessarily improve the fit of the model significantly, but can create a problem of multi-collinearity and can hence reduce the applicability of biomass equations

(Ter-Mikaelian and Korzukhin 1997, Chojnacky 2003, Zianis et al. 2005). A variety of studies have shown that including the height variable didn't improve the R^2 and/or decrease the SSE substantially for biomass estimation (Freedman et al. 1982, Peterson et al. 1970, Schmitt and Grigal 1981, Campbell et at. 1985).

For research purposes, a small increase in precision may sometimes be considered important. In such a situation if height and other variables are available, the use of *DBH*, *HT* and/or *CW* based equations can be considered for better precision. Furthermore if the equations are applied to shortleaf stands in which the relationship between *DBH* and *HT* is different than that in the current dataset, use of the *HT* variable may be advantageous.

Table 9. Fit Index and Root Mean Square Error for equations (22) utilizing *DBH*, *HT* and *CW*.

Tree Component	Equation	Fit Index	RMSE
Bole Wood	$Y = e^{(\beta_{10})} DBH^{(\beta_{11})} HT^{(\beta_{12}+\beta_{19}X_1)}$	0.9762	14.9891
Total Bole	$Y = e^{(\beta_{20}+\beta_{23}X_1)} DBH^{(\beta_{21})} HT^{(\beta_{22})}$	0.9797	15.4637
Branch	$Y = e^{(\beta_{30})} DBH^{(\beta_{31}+\beta_{310}X_3)} CW^{(\beta_{33})}$	0.9053	6.9814
Foliage	$Y = e^{(\beta_{40}+\beta_{46}X_2+\beta_{47}X_3)} DBH^{(\beta_{41})} CW^{(\beta_{43})}$	0.9356	1.0187
Total Tree	$Y = e^{(\beta_{20}+\beta_{23}X_1)} DBH^{(\beta_{21})} HT^{(\beta_{22})} + e^{(\beta_{30})} DBH^{(\beta_{31}+\beta_{310}X_3)} CW^{(\beta_{33})} + e^{(\beta_{40}+\beta_{46}X_2+\beta_{47}X_3)} DBH^{(\beta_{41})} CW^{(\beta_{43})}$	0.9783	22.063

2.4. Conclusion and Recommendations

Biomass equations were developed both at branch and tree levels that can be used to estimate biomass of above-ground tree components for shortleaf pine stands. All relationships were nonlinear power functions. Individual branch biomass (wood and foliage) was closely related to branch basal diameter; i.e., the bigger the branch the larger was its biomass. Location of the branch in crown was also associated with branch biomass. At branch-level the mixed-effect model (Model II) was found to be a more realistic representation of the data than Model I (fitted by OLS) because the Model II considers the correlations among the branch measurements within a tree.

At tree-level, sets of equations based on *DBH* and *DBH*, *HT* and/or *CW* were presented for various tree biomass components (bole wood, total bole (bole with bark), branch and foliage). Parameters were estimated using the nonlinear seemingly unrelated regression (NSUR) method to account for the correlation between components and to assure the additivity property of the biomass components. These models also utilized dummy variables to represent the stand density treatments. Significant dummy variables indicate the existence of an effect of stand density on component biomass. In the case of stem biomass equations the only significant dummy variable was X_1, suggesting that the same biomass equation can be used for all levels of thinning applied in these plots. Adding the crown width variable in the crown biomass equation didn't improve the fit index. Therefore, dummy variables alone were enough to capture the effect of stand density on crown biomass.

No substantial differences in fit statistics were observed between the equations based on *DBH* and the equations based on *DBH*, *HT* and/or *CW*. *DBH*-based equations provide a good balance between accurate prediction and ease of application since they use only *DBH* as a predictor variable. Since the *DBH* can be measured easily, these equations would be the best for forest management practice.

Clearly, the models at branch-level and tree-level presented above fit our biomass data well. Even though these models have been developed for estimating the stand biomass in a study area, they may also be useful for other forestry management purposes in the region. In addition, these models predict the component biomass of a tree from different stand densities using dendrometric variables. Hence, there is no need of fitting equations separately for each level of stand density. However, validation of the equations may be desirable prior to application to other areas. These models are best applied within the ranges of *DBH*s occurring in the parameter-fitting dataset, that is, *DBH*s ranging from 5 cm to 33cm. Since the data for the study were collected during the winter, the foliage biomass equations estimate the foliage from previous growing season, which expected to fall during the fall season of following year.

Literature Cited

Akaike, H. 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control, AC-. 19:716-723.

Berhe, L. 2005. An overview of Mixed Effects Models in Forestry, Statistic Department, Umea University.

Biging, G. S. 1985. Improved estimates of site index curves using a varying-parameter model. Forest Science. 31(1): 248-259.

Budhathoki, C.B., T.B. Lynch, and J.M. Guldin. 2008. A Mixed-Effect Model for the dbh-Height Relationship of Shortleaf Pine (*Pinus echinata* Mill.). South. J. Appl. For. 32(1):5-11.

Burns, R. M., and B. H. Honkala, tech cords. 1990. Silvics of North America. 1. Conifers. Agriculture Handbook 654. Washington, DC: U.S. Department of Agriculture, Forest Service.

Campbell, J.S., V.J. Leffers, and E.C. Pielou. 1985. Regression equations for estimating single tree biomass of trembling aspen: assessing their applicability to more than one population. For. Ecol. Manage. 11:283 –295.

Chojnacky, D.C. 2003. Allometric scaling theory applied to FIA biomass estimation. Forest Inventory Research, Enterprise Unit, USDA Forest Service; 1115-VMPR; 1400 Independence Avenue, Washington.

Clark III, A. and M.A. Taras. 1976. Biomass of shortleaf pine in a natural saw timber stand in northern Mississippi. USDA For, Serv. Res. Paper SE – 146. 32 p.

Clark III, A. 1982. Predicting biomass production in the south. P. 119-139. In: predicting growth and yield in the Mid-South. 31st Annual For. Symp., Hotvedt, J.E., and B.D. Jackson (eds.). Louisiana State University, Baton Rouge, LA. 160p.

de Gier, A. 2003. A new approach to woody biomass assessment in woodlands and shrublands. In: P. Roy (ed.), Geoinformatics for Tropical Ecosystems, Bishen Singh Mahendara Pal Sing, Dehra Dun, India. 161-198.

Dias, A.T.C., E.A. de Mattos, S.A. Vieira, J.V. Axeredo and F.R. Scarano. 2006. Above ground biomass stock of native woodland on a Brazilian sandy coastal plain: Estimates based on the dominant tree species. Forest Ecology and Management. 226(1-3): 364-367.

Ek, A.R. 1979. A model for estimating branch weight and branch leaf weight in biomass studies. For. Sci. 25:303 – 306.

Fang, J., A. Chen, C. Peng, S. Zhao, and L. Ci. 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. Science. 292:2320-2322.

Fehrmann, L. and C. Kleinn. 2006. General considerations about the use of allometric equations for biomass estimation on the example of Norway spruce in central Europe. Forest Ecology and management. 236(2-3): 412-421.

Fowells, H A., comp. 1965. Silvics of forest trees of the US. US department of Agriculture, Agriculture Handbook 271, washinton DC. 762p

Freedman, B., P.N. Duinker, H. Barclay, R. Morash and U. Prager. 1982. Forest biomass and nutrient studies in central Nova Scotia. Can. For. Serv. Marit. For. Res. Cent. Int. Rep. M-X-134: 126p.

Gallant, A.R. 1987. Nonlinear statistical models. John Wiley and Sons, New York. 610p

Green, C., B. Tobin, M. O'Shea, E.P. Farrell and K.A. Byrne. 2005. Above-and belowground biomass measurements in an unthinned stands of Sitka Spruce (*Picea sitchensis* (Bong) Carr.). Eur J. Forest Res. (DOI 10.10007/s10342-005-0093).

Gregoire, T.G., O. Schabenberger and J. Barrett. 1995. Linear modeling of irregularly spaced, unbalanced, longitudinal data from permanent-plot measurements. Can. J. For. Res. 25:137-156.

Kozak, A. 1970. Methods of ensuring additivity of biomass components by regression analysis. For. Chron. 46(5):402-404.

Kutner, M.H., C.J. Nachtsheim and J. Neter. 2004. Applied Linear Regression Models, 4^{th} ed. McGraw-Hill Companies, Inc., New York. 693p.

Lambert, M.C., C.H. Hung, and F. Raulier. 2005. Canadian national tree aboveground biomass equations. Can. J. For. Res. 35:1996-2018.

Lawson, E.R. 1978. Natural regeneration of shortleaf pine. P. 1-5. In: Proc. Symp. Management of pines of the interior south. USDA For. Serv. Res. Agric. Tech. Publ. SA-TP2. Knoxville, TN.

Lawson, E.R. and R.N. Kitchens. 1983. Shortleaf pine. P. 157-161. In: Silvicultural systems for the major forest types of the United States. USDA For. Serv. Res. Agric. Hand. 445p.

Loomis, R.M., R.E. Phrares and J.S. Crosby. 1966. Estimating foliage and branch wood quantities in shortleaf pine. For. Sci. 12(1): 30-39.

Lynch, T.B., A.G. Holley and D.J. Stevenson. 2005. A random-parameter height-dbh model for cherrybark oak. South. J. Appl. For. 29:22–26.

Lynch, T.B., J. Nkouka, M.M. Huebschmann and J.M. Guldin. 2003. Maximum likelihood estimation for predicting the probability of obtaining variable shortleaf pine regeneration densities. For. Sci. 49(4):577-584.

McWilliams, W.H., R.M. Sheffield, M.H. Hansen and T.W. Birch. 1986. The shortleaf resource. In: Proc. Symp. on the Shortleaf Pine Ecosystem. Arkansas Coop. Ext. Ser., University of Arkansas, Monticello, AR. p. 9-25.

Myneni, R. B., J. Dong, C. J. Tucker, R. K. Kaufmann, P. E. Kauppi, J. Liski, L. Zhou, V. Alexeyev and M. K. Hughes. 2001. A large carbon sink in the woody biomass of Northern forests. Published online on December 11, 2001, 10.1073/pnas.261555198 98. (26):14784-14789.

Oklahoma Climatological Survey. 2008. Climate of Oklahoma. [On-line]. Available from: http://climate.ocs.ou.edu. (Accessed May 27, 2008).

Parresol, B.R. 1999. Assessing tree and stand biomass: a review with examples and critical comparisons. Forest Sci. 45: 573-593.

Parresol, B.R. 2001. Additive of nonlinear biomass equations. Can. J. Forest Res. 31:865-878.

Peterson, E.B., Y.B. Chan and J.B. Cragg. 1970. Aboveground standing crop, leaf area, and caloric value in an aspen clone near Calgary. Alberta. Can. J. Bot. 48**:** 1459–1469.

Peterson, J.A., J.R. Seiler, J. Nowak, S.E. Ginn and R.E. Kreh. 1997. Growth and Physiological Responses of Young Loblolly Pine Stands to Thinning. For. Sci. 43(4): 529-534.

Pulkkinen, P. 1991. Crown structure and partitioning of above-ground biomass before the competition phase in a mixed stand of normal crowned Norway spruce (*Picea abies* (L.) Karst.) and pendulous Norway Spruce (*Pecea abies f. pendula* (Lawsan) Sulven). Tree Physiol. 8: 361-370.

Rogers, R. 1983. Guides for thinning shortleaf pine. P. 217-225 in Proc. 2nd Bienn. South. Silv. Res. Conf., Jones Jr., E.P. (ed) USDA For. Serv. Gen. Tech. Rep. SE-24. 514p.

Sabatia, C.O. 2007. Effect of thinning on partitioning of Aboveground biomass in Naturally Regenerated Shortleaf pine (*Pinus echinata* Mill.). M.S. Thesis. Oklahoma State University, Oklahoma. 75p.

SAS Institute Inc. 2002-2004. SAS 9.1.3 Help and Documentation, Cray, NC: SAS Institute Inc.

Schmitt, M.D.C. and D.F. Grigal. 1981. Generalized biomass estimation equations for *Betula papyrifera* Marsh. Can. J. For. Res. 11: 837–840.

Shifley, S.R. 1987. A generalized system of models forecasting central states tree growth. USDA. For. Res. Pap. NC-279. 10p

Ter-Mikaelian, M.T. and M.D. Korzukhin. 1997. Biomass equations for sixty-five North American tree species. For. Ecol. Manage. 97: 1-24.

Willet, R.L. 1986. Foreword. In: Proc. of Symp. on the Shortleaf pine ecosystem, Murphy, P.A. (ed.). Mar. 31–Apr. 2, 1986, Little Rock, AR, 272 p.

Wittwer, R. F., T.B. Lynch, and M.M. Huebschmann. 1996. Thinning Improves Growth of Crop Tree in Natural Shortleaf Pine Stands. South. J. Appl. For. 20(4):182-187.

Wittwer, R. F., T.B. Lynch, and M.M. Huebschmann. 1998. Stand density index for shortleaf pine (*Pinus echinata* Mill.) natural stands. P. 590-596. In Proc 9th Biennial South. Silv. Res. Conf., Waldrop, T.A. (ed). USDA For. Serv. Gen. Tech. Rep. SRS-20.

Zhang, Y., B. Borders, R.E. Will and H. Des Los Santos Pasadas. 2004. A model for foliage and branch biomass prediction for intensively managed fast growing loblolly pine. For. Sci. 50: 65-80.

Zianis, D., P. Muukkonen, R. Makipaa and M. Mencuccini. 2005. Biomass and stem volume equations for tree species in Europe. Silva Fennica (monographs 4): 1-63.

Appendices

Appendix I: Biomass estimates and tree dimension data for each of the sampled trees.

Block	Plot	Tree Number	DBH (cm)	HT (m)	CL (m)	CW (m)	Bole Wood (kg)	Bole Bark (kg)	Total Bole (kg)	Branch (kg)	Foliage (kg)	Total Tree (kg)	Treatment
LP	1	2	23.29	18.15	6.50	6.28	192.42	24.95	217.37	27.46	6.44	251.27	30 FS
LP	1	4	18.89	17.50	5.78	3.98	110.66	11.62	122.28	14.79	3.53	140.60	30 FS
LP	1	5	21.54	17.42	6.54	4.69	147.10	23.02	170.13	28.33	6.41	204.87	30 FS
LP	1	7	30.74	18.29	6.49	7.56	317.62	35.98	353.60	84.27	13.69	451.56	30 FS
PC	2	3	26.95	17.45	5.73	4.51	223.95	27.95	251.90	32.56	5.88	290.35	70 FS
PC	2	4	17.14	15.02	3.11	2.29	72.40	13.39	85.79	5.49	1.47	92.75	70 FS
PC	2	6	21.58	18.01	5.52	4.71	174.22	17.05	191.26	24.85	4.90	221.01	70 FS
PC	2	8	13.79	14.84	2.39	3.35	53.92	7.50	61.42	7.33	2.40	71.15	70 FS
UP	3	1	26.94	18.21	6.32	7.82	237.71	28.69	266.40	29.12	5.77	301.29	50 FS
UP	3	2	23.99	17.76	5.94	6.92	190.04	19.66	209.70	29.77	5.87	245.35	50 FS
UP	3	4	20.44	16.69	5.31	5.23	140.61	15.13	155.74	13.98	4.08	173.81	50 FS
UP	3	6	16.08	15.46	3.02	3.67	78.82	10.22	89.04	5.86	1.55	96.45	50 FS
LP	1	4	20.24	16.66	6.19	3.40	123.64	12.98	136.62	25.60	5.36	167.58	50 FS
LP	1	5	12.80	14.59	2.29	1.28	44.55	5.48	50.03	1.19	0.39	51.61	50 FS
LP	1	10	15.84	15.77	4.57	3.14	70.63	11.54	82.17	5.73	2.28	90.19	50 FS
LP	1	13	28.55	18.36	6.04	5.46	241.51	31.03	272.55	27.35	6.07	305.97	50 FS
PC	2	1	18.09	16.02	5.33	3.02	97.92	11.35	109.27	7.99	3.11	120.37	90 FS
PC	2	21	21.64	16.70	4.84	3.54	128.44	21.61	150.05	13.87	6.02	169.93	90 FS
PC	2	22	4.69	4.54	0.84	0.82	1.90	0.23	2.14	0.08	0.09	2.31	90 FS
PC	2	109	29.54	17.37	6.62	7.00	249.07	36.08	285.15	43.45	9.92	338.52	90 FS
UP	3	1	26.80	18.80	6.08	7.04	248.50	28.05	276.55	41.25	9.30	327.10	30 FS
UP	3	3	28.54	18.71	6.96	7.73	273.03	29.09	302.12	49.62	9.24	360.98	30 FS
UP	3	4	33.25	19.06	8.97	8.15	368.98	41.83	410.81	103.70	17.92	532.43	30 FS
UP	3	19	19.34	16.76	6.66	4.40	125.43	14.15	139.58	15.85	3.40	158.83	30 FS
LP	1	45	28.34	19.31	7.20	4.88	241.31	26.94	268.26	36.40	8.17	312.83	90 FS
LP	1	78	13.94	18.24	9.94	1.75	57.75	7.66	65.41	3.63	1.59	70.62	91 FS

Appendix I (Continued)

Block	Plot	Tree Number	DBH (cm)	HT (m)	CL (m)	CW (m)	Bole Wood (kg)	Bole Bark (kg)	Total Bole (kg)	Branch (kg)	Foliage (kg)	Total Tree (kg)	Treatment
LP	1	91	2.80	4.86	1.86	0.81	0.81	0.18	0.99	0.09	0.10	1.18	92 FS
LP	1	252	8.34	11.02	6.00	1.06	13.22	1.96	15.17	0.65	0.30	16.13	93 FS
PC	2	1	23.19	15.88	5.97	6.07	154.39	21.86	176.25	35.25	8.00	219.50	30 FS
PC	2	3	23.54	16.20	5.35	5.33	168.88	20.57	189.45	21.03	6.10	216.58	30 FS
PC	2	6	27.04	17.27	6.75	7.42	245.67	25.02	270.68	44.70	9.25	324.64	30 FS
PC	2	11	18.14	15.92	5.38	3.31	101.21	14.97	116.18	11.94	3.62	131.73	30 FS
UP	3	2	9.66	13.64	3.29	1.66	19.26	3.26	22.52	1.18	0.48	24.18	90 FS
UP	3	6	18.59	17.25	4.82	2.85	90.90	14.15	105.05	7.97	3.27	116.29	90 FS
UP	3	45	12.48	13.67	2.22	1.48	28.43	5.00	33.43	2.28	0.88	36.59	90 FS
UP	3	52	22.34	17.00	5.35	5.15	183.36	20.21	203.57	28.40	7.40	239.37	90 FS
LP	1	6	20.14	16.87	5.43	4.65	122.95	12.59	135.54	12.04	3.03	150.60	70 FS
LP	1	18	12.10	16.76	3.06	2.04	47.46	4.84	52.30	1.45	0.70	54.45	70 FS
LP	1	30	12.64	14.19	4.86	2.11	41.62	5.08	46.70	2.58	0.83	50.11	70 FS
LP	1	53	30.05	18.01	7.39	6.69	262.77	32.05	294.82	43.50	8.58	346.90	70 FS
PC	2	1	11.99	14.56	6.43	3.28	44.33	4.89	49.22	3.60	1.24	54.06	50 FS
PC	2	3	23.69	17.77	4.12	3.41	155.62	23.64	179.26	11.60	3.77	194.63	50 FS
PC	2	6	19.04	17.34	4.50	3.55	119.64	16.10	135.74	10.28	2.71	148.73	50 FS
PC	2	39	15.43	13.74	3.77	3.35	47.98	9.50	57.48	2.96	1.47	61.91	50 FS
UP	3	1	11.28	11.50	2.71	1.55	27.79	4.86	32.66	1.50	0.74	34.90	70 FS
UP	3	9	32.14	16.57	6.74	6.63	326.57	49.75	376.31	62.41	11.17	449.90	71 FS
UP	3	17	23.94	18.17	4.97	4.47	176.76	16.92	193.68	31.13	6.22	231.03	72 FS
UP	3	24	28.74	18.27	5.84	5.70	216.81	35.92	252.73	27.42	6.54	286.69	73 FS

Appendix II: Branch-level equations Residual Plots.

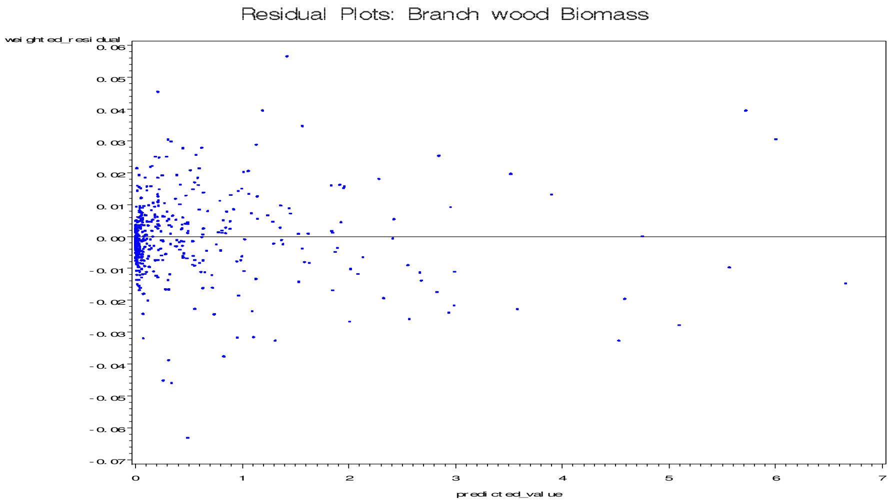

Figure: Residual plot for Branch wood biomass

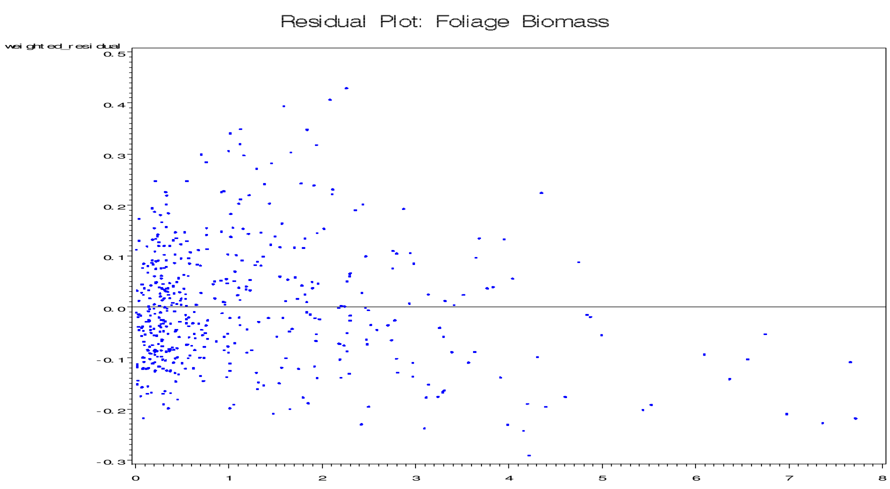

Figure: Residual plot for Branch foliage biomass

Appendix III: Tree-Level Equation Residual Plots.

a) Residual plots for DBH based equations, fitted in system of equations (17).

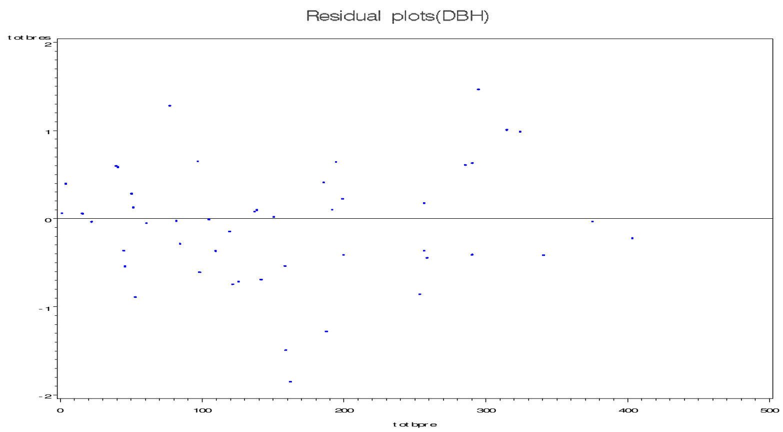

Figure: Residual Plot for bole wood biomass equation.

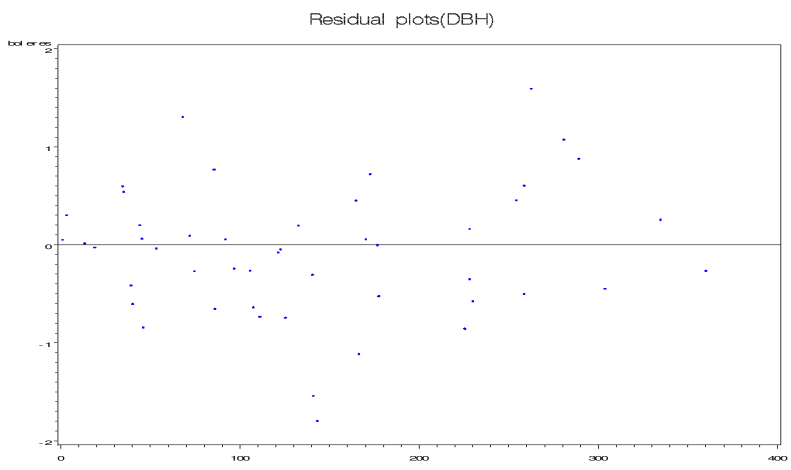

Figure: Residual Plot for total bole biomass equation.

Appendix III (Continued)

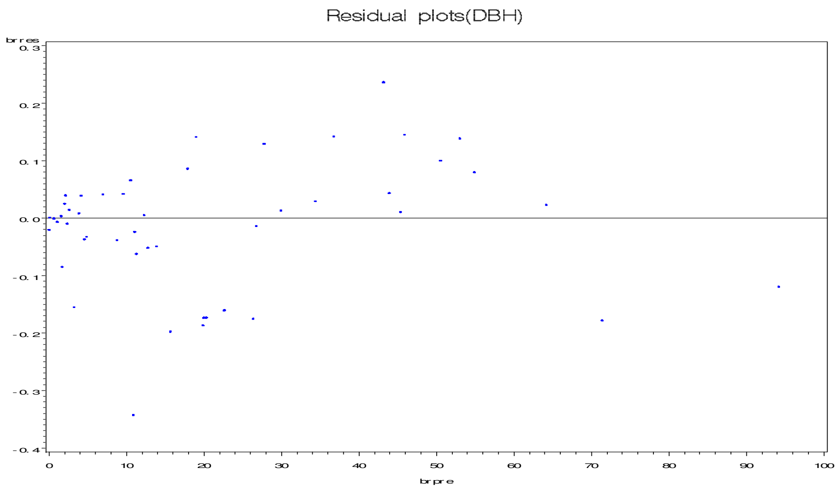

Figure: Residual Plot for branch biomass equation.

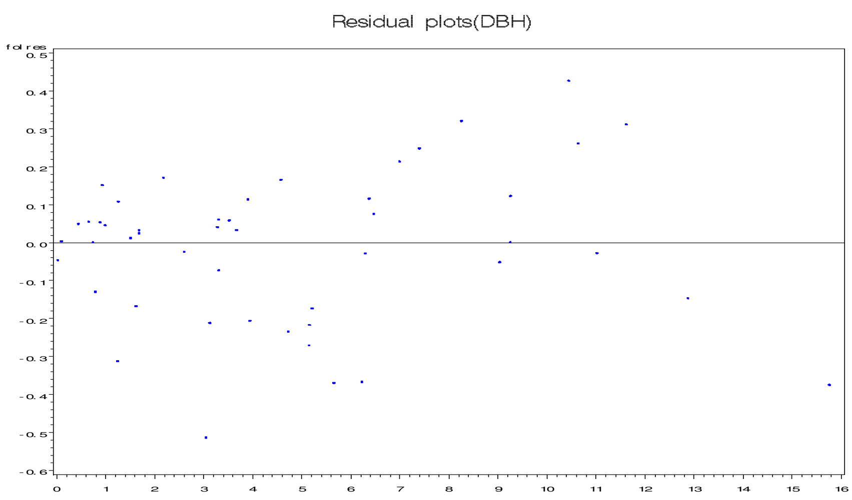

Figure: Residual Plot for foliage biomass equation.

Appendix III (Continued)

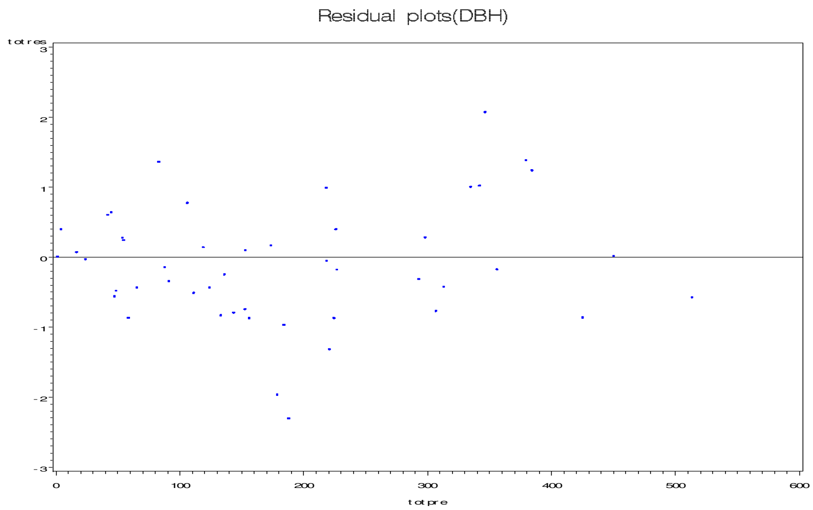

Figure: Residual Plot for total tree biomass equation.

b) Residual plots for DBH, HT and/or CW based equations, fitted in system of equations (22).

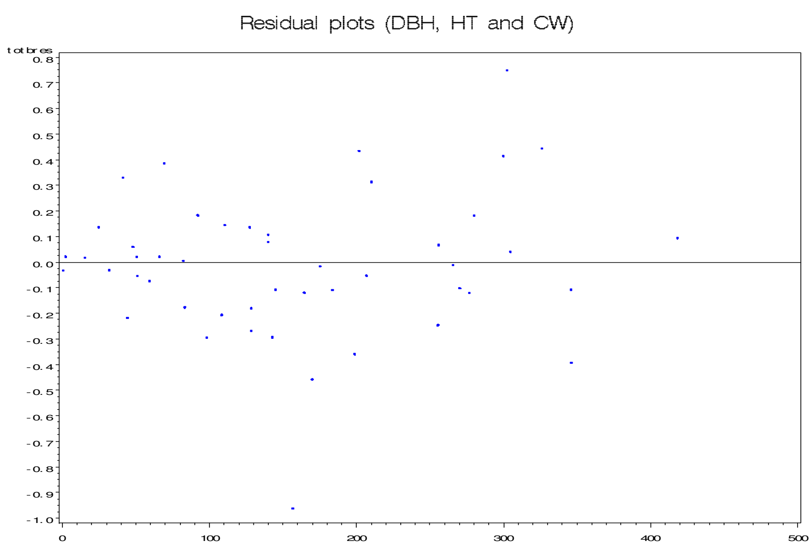

Figure: Residual Plot for bole wood biomass equation.

Appendix III (Continued)

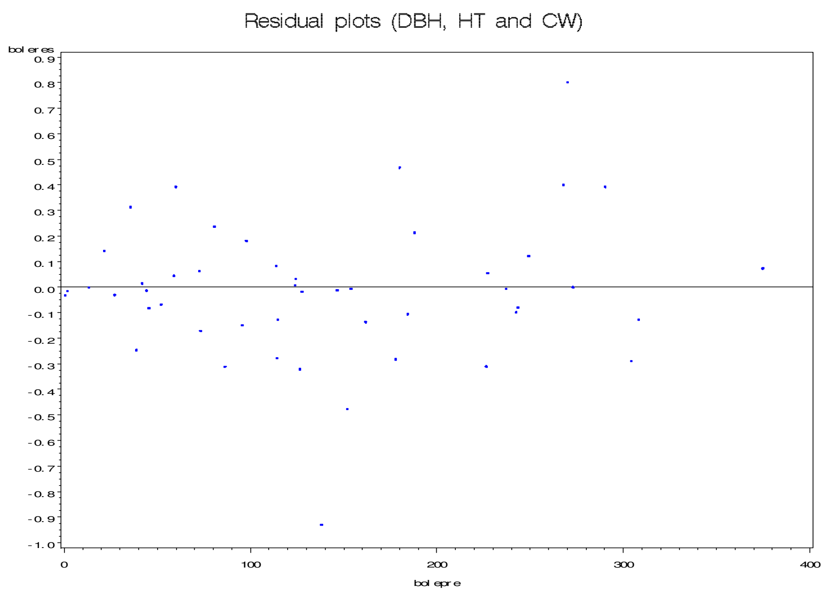

Figure: Residual Plot for total bole biomass equation.

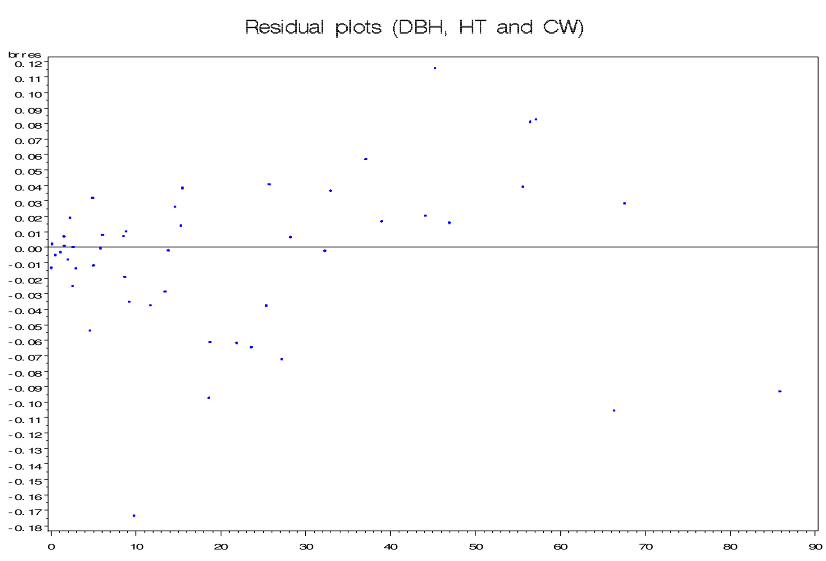

Figure: Residual Plot for branch biomass equation.

Appendix III (Continued)

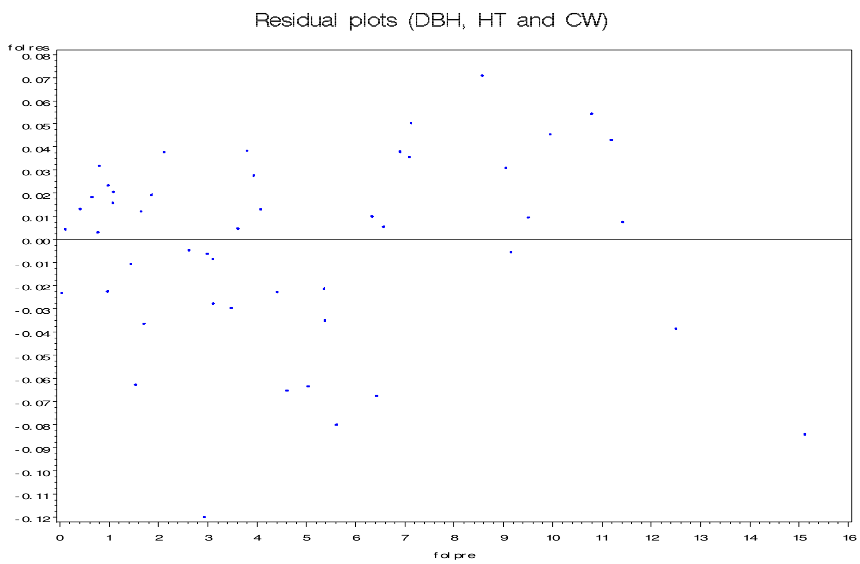

Figure: Residual Plot for foliage biomass equation.

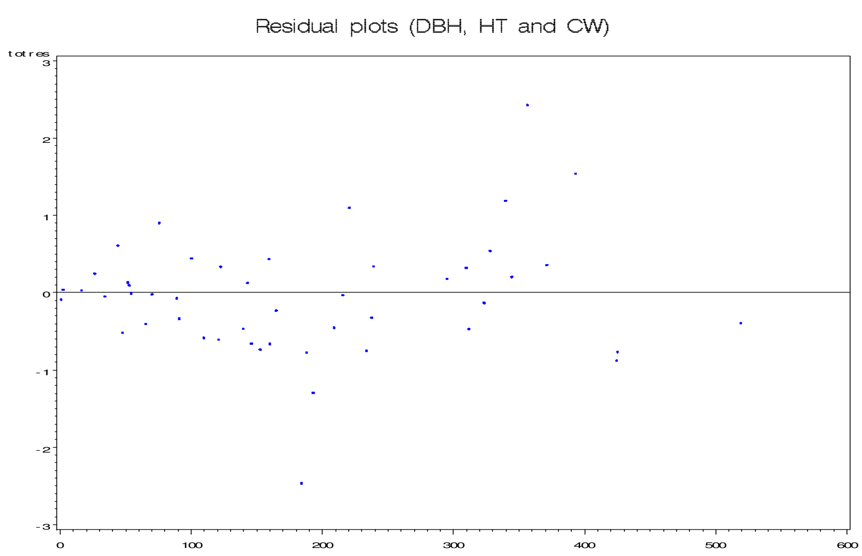

Figure: Residual Plot for total tree biomass equation.

CHAPTER III

MANUSCRIPT II

EFFECTS OF THINNING ON ABOVE GROUND TREE COMPONENT BIOMASS PARTITIONING IN NATURALLY REGENERATED SHORTLEAF PINE (*Pinus echinata* Mill.) STANDS

Abstract

The effects of thinning on tree biomass components of approximately 40-50 year-old shortleaf pine (*Pinus echinata* Mills.) stands on two sites in southeast Oklahoma were analyzed. These naturally regenerated stands were thinned during 1989-1990. Thinning treatments included unthinned control plots and plots thinned to 70%, 50%, and 30% of full stocking. Total tree and bole wood biomass in thinned plots were found to be converging towards their unthinned counterparts. For example, the thinning to 70% of full stocking treatment has already exceeded the biomass contained in its unthinned counterpart on site one in 16 years. However, heavily thinned stands may take much longer to converge. Foliage and bark biomass reduced with an increase of thinning intensity. The proportion of biomass partitioned to branches and bark was significantly affected by thinning. Unless heavily thinned, thinning treatments did not significantly affect the proportion of biomass allocation to bole. Although thinning seemed to reduce the total foliage biomass, it seemed that heavily thinned stands increase in terms of proportion of foliage to total biomass; however it was not statistically significant. Better site quality was associated with allocation of more biomass to bole wood and less to foliage.

3.1. Introduction

Thinning is a common silvicultural practice in forest management used to regulate stand density and to increase diameter growth. According to the Society of American Foresters (1958), " thinning is a cutting in an immature stand which is done to increase the growth rate, to foster quality growth, improve composition, to promote sanitation, and/or to recover and use material that would otherwise be lost to mortality". Thinning does not generally increase per-hectare cubic-volume growth, but it can increase merchantable (e.g. board-foot) yield. Though foresters most commonly thin stands to enhance wood production, they can also use thinning to control conditions of essential plant and animal habitats, or to enhance other nonmarket values (Nyland 1996). Thinning improves environmental conditions for residual trees by reducing competition between plants and increasing the amount of available nutrients, water and light (Daniel et al. 1979, Wittwer et al. 1996). Thinning intensity generally refers to the amount of growing stock left in place after cutting. Measurements of the residual trees are often used to characterize the growth response after thinning. Studies have shown that thinning mainly increases the bole diameter (Wittwer et al. 1996, Phipps 1973) and crown area of the residual trees (Peterson et al. 1997). This change in relationship in tree components growth due to thinning, likely results in changes in biomass partitioning to tree components. In this study partitioning refers to the allocation of biomass to standing biomass of aboveground tree components.

Plant biomass partitioning is of great importance to the study of forest productivity. The main focus of production has usually been to maximize allocation of biomass to merchantable stem wood. Woody biomass in forest stand is more important than foliage biomass also in carbon sequestration. Information relating to biomass partitioning in a particular stand density also provides information on existing fuel loads. This information is a prerequisite for prescribed fire management in forestry.

Several studies have reported the relationship between the thinning intensity and growth of diameter and volume in shortleaf pine (Phipps 1973, Rogers 1983, Wittwer et al. 1996) but relatively little is known about how stand density affects biomass partitioning to various tree components. However, Baldwin et al. (2000) and Burkes et al. (2000) have reported on the effects of stand density on biomasses partitioning to stand components in loblolly pine. The purpose of the present study was to investigate how thinning affects the partitioning of biomass to different tree components (bole wood, bole bark, branches and foliage) in naturally regenerated even-aged shortleaf pine.

3.1.1. Objectives of Study

i) To determine the per hectare biomass in bole wood, bole bark, branches, and foliage in experimental plots thinned to 30% of full stocking, 50 % of full stocking , 70 % of full stocking and unthinned control plots.

ii) To compare the biomass components among the four stand densities.

iii) To compare the effects on biomass portioning of two site qualities, one a relatively poor site and the other a relatively better site for natural shortleaf pine in the region in which the study was conducted.

3.2. Methods and Materials

3.2.1. Study area

The study was conducted on two sites in natural shortleaf pine stands in the Ouachita Mountains of Pushmataha County, southeast Oklahoma. Study sites were located on industrial forest lands owned by Plum Creek Timber Company. Site one is located about 35 miles northwest of site two (Wittwer et al. 1998). Detailed information about site one is given in manuscript I. According to the USDA-SCS soil survey, site two falls in the Sherwood (Fine-loamy, mixed, semiactive, thermic Typic Hapludults) –Zafra (Loamy-skeletal, siliceous, semiactive, thermic Typic Hapludults) association. The site index, at age of 50 years, was 22.25 meters for this site, which is better than site one. The soil series at both sites are formed from shale and sandstone and are deep and well-drained (Bain and Watterson 1979 cited in Wittwer et. al. 1996).

3.2.2. Sampling Design

Sample plots were established during the period 1989-1990. At site one the stands were 25-30 years old while trees were 30-35 years old at site two at the time of establishment (Wittwer et al. 1998). At site one, twelve square treatment plots of 0.16 ha were distributed among three blocks. Within each of these treatment plots a 0.04 ha measurement plot was established. At site two, there were 9 treatment plots of 0.24 ha distributed among three blocks with a 0.08 ha measurement plot. Each treatment plot in both sites was surrounded by a 10 m wide isolation strip. One of the measurement plots in site two had been reduced to 0.04 ha due to inadvertent cutting after application of treatments in the portion of the plot eliminated. The Randomized Complete Block

Design, with blocks nested within sites, was used to test for differences among treatments.

3.2.3. Treatment Design

The treatments prescribed were the application of different density levels. The density levels were: thinned to 30 percent of full stocking (30 FS), thinned to 50 percent of full stocking (50 FS), thinned to 70 percent of full stocking (70 FS) and unthinned control (CONTROL). Each plot in a block from site one was randomly assigned to receive one of the three thinning treatments or was left to serve as an unthinned control. Similarly, each plot in a block from site two was also randomly assigned to receive one of the two thinning treatments or was left to serve as an unthinned control. The two thinning treatments at site two were 50 FS and 70 FS. Since there was no 30 FS treatment at site two, there were unequal treatment levels within the sites. These treatment levels were described based on the shortleaf pine stocking guide developed by Rogers (1983). Low thinning was the thinning technique employed, in which trees were removed from the lowest crown class first, with removals progressing to trees in higher crown classes as thinning intensity increased (Wittwer et al. 1998). Assignment of treatments to plots and some characteristics of the experimental plots are given in Table 1.

Table 1. Assignment of treatments to the plot, and some characteristics of the plots (Year 2006).

Site	Block	Plot	Treatment	Trees/ha	Quadratic Mean *DBH* (cm)	Basal Area (m^2/ha)
One	LP	1	30FS	563	25.3	28
	LP	2	50FS	854	23.3	36
	LP	3	CTRL	1860	17.7	46
	LP	4	70FS	1408	19.7	43
	PC	1	70FS	1123	21.3	40
	PC	2	CTRL	2400	16.1	49
	PC	3	30FS	681	24.0	31
	PC	4	50FS	861	22.3	33
	UP	1	50FS	865	22.8	35
	UP	2	30FS	452	26.8	25
	UP	3	CTRL	1703	16.8	37
	UP	4	70FS	1076	22.9	44
Two	D	1	50FS	540	27.9	33
	D	2	CTRL	1756	19.9	54
	D	3	70FS	935	24.4	44
	E	1	50FS	630	26.4	35
	E	2	70FS	740	25.1	37
	E	3	CTRL	1148	22.4	45
	W	1	50FS	518	28.4	33
	W	2	70FS	802	25.3	40
	W	3	CTRL	1452	20.8	50

LP, PC, UP are three blocks in site one; E, W, D are three blocks in site two; 30FS, 50FS, 70FS and CTRL (control) are four levels of treatments.

3.2.4. Estimation of Biomass Components

Biomass data were obtained from pre-established study plots from two sites using allometric equations derived from destructive sampling. For site one, *DBH* (diameter at breast height), height (*HT*) and crown width (*CW*) measurement from the plot inventory in 2006 were used to determine the tree and tree component biomass for each tree using the following system of equations developed in Manuscript I.

$$Y_{BOLEWOOD} = e^{-3.91542} DBH^{1.95453} HT^{1.01546-0.03696 X_1} \tag{1}$$

$$Y_{TOTALBOLE} = e^{-3.44778-0.09825 X_1} DBH^{1.96841} HT^{0.87753} \tag{2}$$

$$Y_{BRANCH} = e^{-6.16769} DBH^{2.59124-0.08006 X_3} CW^{0.73434} \tag{3}$$

$$Y_{FOLIAGE} = e^{-5.33157-0.13788 X_2 -0.29838 X_3} DBH^{2.08693} CW^{0.35026} \tag{4}$$

where,

Y_i is tree component biomass (kg), i = bole wood, total bole, branch or foliage,

DBH is diameter at breast height (cm),

HT is total height of the tree (m),

CW is crown width (m), and

X_1, X_2 and X_3 are dummy variables representing stand densities, where X_1= 1 for unthinned stand and zero other wise; X_2= 1 for 70 FS and zero other wise; and X_3 =1 for 50 FS and zero otherwise.

Total tree biomass was obtained by adding the estimated total bole, branch and foliage biomass obtained from equations (2), (3) and (4), respectively. Bark biomass was determined by subtracting estimated bole wood biomass from total bole biomass. Since these equations were fitted by the nonlinear seemingly unrelated regression (NSUR) method as a complete system along with the total biomass, the sum of predicted biomass components is constrained to be equal to total biomass. Individual total tree biomasses were summed to obtain total plot biomass expressed on a per hectare basis.

For site two, component biomasses were obtained from the study conducted by Sabatia (2007). He used the following system of equations to estimate the tree and tree component biomass.

$$Y_{BOLEWOOD} = e^{-3.47996} DBH^{1.984397} HT^{0.814912-0.02202 X_1} \tag{5}$$

$$Y_{TOTALBOLE} = e^{-3.60433} DBH^{1.956015} HT^{0.913537-0.01347 X_1} \tag{6}$$

$$Y_{BRANCH} = e^{-6.94109} DBH^{2.636473} CW^{0.879174} \tag{7}$$

$$Y_{FOLIAGE} = e^{-4.73214} DBH^{1.707013} CW^{0.447436} \tag{8}$$

where,

Y_i is tree component biomass (kg), i = bole wood, total bole, branch or foliage,

DBH is diameter at breast height (cm),

HT is total height of the tree (m),

CW is crown width (m), and

X_1 is a dummy variable, where X_1=1 for unthinned stand and zero for thinned stands.

These equations had also been fitted by NSUR method. Component biomasses per hectare were calculated in similar manner as described above for site one. The reason for selecting the equations based on *DBH*, *HT* and/or *CW* for site one biomass estimation was to make it consistent with the biomass estimation in site two, where similar form of equations were used for estimation. In manuscript I it was found that systems of equations based on the independent variable *DBH* alone (together with dummy variables indicating thinning treatments) had fit statistics very similar to a system of biomass equations based on independent variables including *DBH*, *HT* and/or *CW* together with dummy variables indicating thinning. Therefore, either one of these sets of equations would give reliable biomass estimation. Tree and tree component biomasses for each of the study plots expressed on per hectare basis for both sites are given in Appendix I.

3.2.5. Statistical Analysis

A randomized complete block design, with block being nested in site, was used to perform the analyses of variance in order to test whether the treatment responses were significantly different. Analysis of variance (ANOVA) was performed using the mixed model (MIXED procedure), with Restricted Likelihood (REML) estimation in SAS/STAT® software, Version 9.1.3 (SAS Institute Inc. 2000-2004). The response variables examined were quadratic mean diameter and basal area per hectare (Table 1), per hectare biomass estimates for the trees and tree components (bole wood, bark, branches and foliage) (Appendix I), and the proportion of component biomass to the total plot biomass (Appendix II). Before performing the ANOVA with biomass proportions, arcsine square root transformations were applied to proportions to ensure equality of variance among treatments.

Since site by treatment interactions were significant, the interaction model was used for Analysis of Variance to test simple effects of site and treatment. The multiple comparisons (Tukey's procedure) were conducted by using SLICE option under

LSMEANS statement in the SAS MIXED procedure. The syntax and commands for SAS procedures are given below.

```
PROC MIXED DATA=file name COVTEST;
CLASS SITE BLOCK TREATMENT;
MODEL dependent variable= SITE*TREATMENT /DDFM=KR;
RANDOM BLOCK(SITE);
LSMEANS SITE*TREATMENT/PDIFF ADJUST=TUKEY SLICE = (SITE
TREATMENT);
RUN;
```

where, SITE and TREATMENT were fixed effects and BLOCK was a random effect. The purpose to the study was to test the simple effects of thinning treatments and sites. The multiple comparisons of means were made using the Tukey's HSD adjustment.

3.3. Results and Discussion

Tables 2a and 2b present the average number of trees, average tree sizes and mean basal areas in study areas in years 2006 and 1988/89, respectively. Average number of trees, average tree sizes and mean basal areas varied between treatments for both sites (Table 2). Unthinned CONTROL plots contained significantly more trees than any of the thinned treatments but the mean trees per hectare for 50 FS and 70 FS did not differ significantly from each other on either site ($\alpha<0.05$). In site one, the mean number of trees from 30 FS was significantly smaller ($\alpha<0.05$) than 70 FS but it was not significantly different from 50 FS. These insignificant differences between 30 FS and 50 FS, and 50 FS and 70 FS, may be due to higher levels of mortality in lightly thinned stands compared to lower mortality in the slight heavily thinned stands. Wittwer et al. (1996) has also mentioned that the mortality increases with the decreasing intensity of thinning level.

Table 2a. Trees/ha, quadratic mean diameter (QDM) and Basal (BA) area by site and treatments in 2006.

Site	Treatment	Stocking (%)	Trees/ha	S.E.[1]	Quadratic mean DBH (cm)	S.E.	Basal Area m^2/ha	S.E.
One	30 FS	79.7	565 a	114.5	25.9 a	1.3	28.2 a	2.7
	50 FS	102.5	860 a b	5.5	22.8 a b	0.5	35.2 a b	1.4
	70 FS	126.7	1202 b	179.6	21.3 b	1.5	42.5 b	2.0
	CONTROL	144.8	1987 c	365.6	16.9 c	0.8	44.2 b	5.9
Two	30 FS	-NA-	-NA-	-NA-	-NA-	-NA-	-NA-	-NA-
	50 FS	90.2	562 a	59.3	27.6 a	1.0	33.7 a	1.1
	70 FS	113.6	825 a	99.6	24.9 a	0.4	40.3 ab	3.5
	CONTROL	148.2	1452 b	304.0	21.0 b	1.2	49.7 b	4.5

[1] Standard Error. Means within the same column in each site indicated by the same letter a, b, or c; are not significantly different at $P \leq 0.05$.

Table 2b. Trees/ha, quadratic mean diameter (QDM) and Basal (BA) area by site and treatments in 1988/89.

Site	Treatment	Stocking (%)	Trees/ha	Quadratic mean DBH (cm)	Basal Area m^2/ha
One	30 FS	30.6	565	15.0	8.5
	50 FS	48.4	898	18.0	13.5
	70 FS	67.7	1252	14.0	18.9
	CONTROL	175.8	7245	8.0	36.9
Two	30 FS	-NA-	-NA-	-NA-	-NA-
	50 FS	50.9	567	19.0	16.0
	70 FS	70.9	850	18.3	22.3
	CONTROL	148.9	2287	15.1	40.5

Following a pattern similar to that described above for the number of trees per hectare, quadratic mean *DBHs* (QMD) of trees in thinned plots were significantly different from those in unthinned plots for both sites ($\alpha<0.05$). The average QMD for the 30 FS was significantly larger than for the 70 FS ($\alpha<0.05$). Although not significant, the QMD for 30 FS was also larger than that for 50 FS. The significantly greater QMD growth in the trees growing in thinned plots suggests that thinning is useful if the objective is to have the larger trees. Low density stands also allow the growth of understory vegetation (McConnell and Smith 1970, Thomas et al. 1999) that may be favorable habitat for some wildlife (Suzuki and Hayes 2003).

The mean basal areas per hectare in unthinned control plots were significantly higher than for the 30 FS thinned treatment in site one and 50 FS thinning treatment in site two ($\alpha<0.05$). There was no significant difference in mean basal area per hectare between light and intermediate thinned treatments, 50 FS and 70FS. However, mean basal area per hectare in the 70 FS was significantly greater than in the 30 FS for site one. Table 3 presents the mean basal area by treatment in year 1988/89 and Table 4 presents the net basal area growth after 16 years of thinning. It is clear that the thinned treatments have bigger net growth rates than their unthinned counterparts. Among all thinned treatments, thinned to 70 % full stocking had the greatest basal area growth. The insignificant difference of the mean BA/ha in 2006 between 70 FS and CONTROL suggests that the basal area for these two densities started converging. This evidence is also supported by the fact that the basal area growth in 70 FS is much higher (23.6m^2/ha in site one and 18m^2/ha in site two) compared to unthinned CONTROL plot (7.9m^2/ha in site one and 9.2m^2/ha in site two) during 16 years post thinning. Greater basal area growth in thinned plots is due to lower competitive pressure. The basal area growth of thinned shortleaf pine stands seemed to be converging towards their unthinned counterparts as shown by its greater growth due to thinning; although there was no evidence that the basal area of thinned plot will exceed the unthinned plots. Similar trends were also observed by a previous study by Hasenauer et al. (1997) and Baldwin et al. (2000) in loblolly pine stand.

Table 3. Mean basal area by treatments for year 1988/89 (Wittwer et al. 1998).

Site	Treatment	30 FS	50 FS	70 FS	CONTROL
One	BA(m^2/ha)	8.5	13.5	18.9	36.3
	STANDARTD ERROR	0.42	0.13	0.80	2.17
Two	BA(m^2/ha)	-NA-	16.0	22.3	40.5
	STANDARD ERROR		0.3	0.4	1.4

Table 4. Basal area growth after 16 years of thinning by treatments for two sites.

Site	Thinning Treatments			
	30 FS	**50 FS**	**70 FS**	**CONTROL**
One	19.7	21.7	23.6	7.9
Two	-NA-	17.7	18	9.2

Mean total tree biomass and component biomass by treatment levels are presented in Table 5. Thinning treatments significantly affected bole wood and total biomass of shortleaf pine stands (site one: *P*-value= 0.0013; site two: *P*-value=0.0014). Mean bole wood and mean total tree biomass was larger for lightly thinned (70 FS) or unthinned stands and gradually decreased with increased thinning intensity. The 30 FS and 50 FS thinning treatments contained significantly less bolewood and total tree biomass than unthinned controls in site one and site two respectively ($\alpha<0.05$). Several studies have found that the thinning does not increase total volume production in southern pine forest stands (Stephen and Jokela 1992, Nebeker et al. 1985). Hamilton (1976) also found there was no significant difference in total volume production in Norway spruce under four different level of thinning treatment. Similarly, Baldwin et al. (2000) did not find sufficient evidence to state that the biomass production in stands of varying densities will converge through time in loblolly pine study. This argument is supported by the results from site two where unthinned plots had large total tree and bole wood biomass. But there are also other studies where convergence of yield production in even aged stands of different densities has been reported (Borders 1984, Baldwin and Feduccia 1987). Phipps (1973) observed that lightly thinned stands produced a slight increase in yield in shortleaf pine plantations in Indiana. Greater mean biomass production in 70 FS in site two supports these studies. Therefore, we can say unthinned or lightly thinned stands can both produce substantial biomass in shortleaf pine.

Table 5. Per hectare biomass components by site and treatments.

Site	Treatment	Mean Component Biomass And Standard Error (S.E.) of Means				
		Bole Wood (kg/ha)	**Bark (kg/ha)**	**Branch (kg/ha)**	**Foliage (kg/ha)**	**Total Tree (kg/ha)**
One	30 FS	107,677 a (SE:4,410)	14,009 a (SE:798)	19,273 ab (SE:715)	4,270 ab (SE:141)	145,229 a (SE:4,530)
	50 FS	134,484 ab (SE:5,103)	17,400 ab (SE:350)	15,084 a (SE:783)	3,630 a (SE:117)	170,598 ab (SE:6,118)
	70 FS	162,738 b (SE:6,321)	21,037 b (SE:591)	20,690 b (SE:1137)	4,884 b (SE:173)	209,348 b (SE:8,157)
	CONTROL	150,141 b (SE:12,607)	20,745 b (SE:1,868)	16,020 ab (SE:1,681)	5,158 b (SE:479)	192,064 b (SE:16,210)
Two	50 FS	157,380 a (SE:6,765)	14,320 a (SE:1,285)	17,927 a (SE:1310)	3,165 a (SE:55)	192,792 a (SE:7,094)
	70 FS	184,497 ab (SE:8322)	16,752 a (SE:670)	17,720 a (SE:509)	3,637 a (SE:181)	222,607 ab (SE:9,662)
	CONTROL	210,231 b (SE:8,922)	25,554 b (SE:955)	14,929 a (SE:484)	3,922 a (SE:143)	254,636 b (SE:10,370)

Means within the same column in each site indicated by the same letter a, b, or c; are not significantly different at $P \leq 0.05$.

Branch biomass for these shortleaf pine stands was found to be greater for thinned treatments. However, the thinning effects were not significant in site two and in site one only 50 FS was significantly different from 70 FS. In site two, greater thinning intensity corresponded to greater branch biomass. However, this did not occur in site one, where the 70 FS thinning treatment had a greatest mean branch biomass followed by the 30 FS. At tree-level several authors have found that with increases in thinning intensity the number of branches and branch biomass increases (Bartelink 1998, Baldwin et al., 2000, Kellomäki et al., 1989). This should result in an increase in the branch biomass at stand-level. Therefore, this exception of smaller mean branch biomass in the moderately thinned (50 FS) treatment (site one) could be due to its inability to offset large reduction in branch biomass during thinning by the increased growth after thinning. Kramer and Kozlowski (1960) have explained that larger branches in heavily thinned stands are needed to support increased amounts of foliage per tree produced in lower stand densities.

Mean foliage biomass was found to be greater for unthinned CONTROL treatments (Table 5) when compared to thinned treatments. However, the differences were not significant; with one exception in site one, where 50 FS was significantly smaller than the control and the 70 FS. Bartelink (1998) has found thinning decreased the biomass partitioning to foliage sharply. But Blevins (2005) observed that thinning increased tree-level foliage biomass and growth efficiency by concentrating limited resources onto fewer trees. In the current study, stand level foliage reduced by the thinning might be due to the large reduction in stocking.

Thinning effects on stand level bark standing biomass were significant in both sites (Table 5). The 30 FS in site one and the 50 FS and 70 FS in site two had significantly smaller biomass partitioned to bark when compared to unthinned CONTROL treatment.

It was not surprising that unthinned stand had larger bark biomass because CONTROL stands had large number of trees. However, we could expect thinning could increase bark biomass at individual tree level as *DBH* increased with thinning. Again, further study at tree-level is needed to investigate this assumption.

Comparison of mean proportions of biomass components to total biomass by treatment levels are presented in Table 6. The proportion of bole wood to the total biomass of a stand was not significantly different among treatments in site two. The mean proportion of bole wood to total biomass was significantly different in only the heavily thinned (30 FS) treatment in site one which was significantly smaller than the other treatments at the 0.05 level. This result suggests that thinning does not significantly affect biomass allocation in bole wood unless the stand is heavily thinned (thinned to 30 % of full stocking). Comparisons of mean branch biomass proportion presented in Table 6 support the trend of increased branch biomass in thinned stands, since the most heavily thinned stands in site one (30 FS) and site two (50 FS) had significantly larger branch biomass proportions than unthinned control treatment. Proportion of foliage biomass partitioning was larger, although not statistically significant from CONTROL, for 30 FS in site one and 50 FS in site two. This supports the previous argument that heavily thinned stands increase the biomass partitioning to foliage. Further tree-level study is needed to explain the cause and actual effects of thinning treatments on foliage biomass. Thinned stands (30 FS in site one and 50 FS and 70 FS in site two) partitioned a significantly smaller proportion of total biomass to bark. Larger proportions of bark to the total biomass in unthinned stands can be explained by larger number of small size trees, which have a larger surface area to volume ratio compared to smaller number of large size trees in thinned stands.

Table 6. Percentage (proportion×100) of component biomass in a plot by treatments and site.

Site	Treatment	Mean Proportion And Standard Error (S.E.) of Means			
		Bole Wood	**Bark**	**Branch**	**Foliage**
One	30 FS	74.1 a (SE:0.94)	9.6 a (SE:0.31)	13.3 a (SE:0.87)	2.9 a (SE:0.085)
	50 FS	78.8 b (SE:0.26)	10.2 ab (SE:0.21)	8.8 b (SE:0.28)	2.1 b (SE:0.034)
	70 FS	77.7 b (SE:0.16)	10.1 ab (SE:0.16)	9.8 b (SE:0.16)	2.3 b (SE:0.034)
	CONTROL	78.2 b (SE:0.70)	10.8 b (SE:0.15)	8.3 b (SE:0.45)	2.7 a (SE:0.094)
Two	50 FS	81.6 a (SE:0.65)	7.4 a (SE:0.39)	9.4 a (SE:0.91)	1.6 a (SE:0.08)
	70 FS	82.9 a (SE:0.15)	7.5 a (SE:0.05)	7.9 ab (SE:0.22)	1.6 a (SE:0.02)
	CONTROL	82.5 a (SE:0.18)	10.0 b (SE:0.10)	5.9 b (SE:0.15)	1.5 a (SE:0.018)

Means within the same column in each site indicated by the same letter a, b, or c; are not significantly different at $P \leq 0.05$.

The simple effect of site was studied on standing biomass components for each treatment separately (Table 7). Although site two had larger mean bole wood and total tree stand biomass than site one for all thinning treatments levels (30 FS, 70 FS and CONTROL), the difference was only significant for the control plots (*P* value = <0.001). Larger total above ground biomass in site two was expected because site two has a higher site index value ($SI_{site\ one}$:17m; $SI_{site\ two}$:22m both at base age 50 yrs). Mean branch and bark biomasses were not significantly different between two sites for any of the treatments levels. Mean foliage biomass was significantly larger in site one for 70 FS and CONTROL treatments. Mean foliage biomass was also larger in site one for 50 FS treatments stands; although not significant. This result indicates that the poor site (site one) might have allocated more biomass to foliage.

Table 7. Mean component biomass by site on different treatment levels.

Treatment	Site	Mean Component Biomass And Standard Error (S.E.) of Means				
		Bole Wood (kg/ha)	**Bark (kg/ha)**	**Branch (kg/ha)**	**Foliage (kg/ha)**	**Total tree (kg/ha)**
50 FS	One	134,484 a	17,400 a	15,084 a	3,630 a	170,598 a
		(SE:5,103)	(SE:350)	(SE:783)	(SE:117)	(SE:6,118)
	Two	157,380 a	14,320 a	17,927 a	3,165 a	192,792 a
		(SE:6,765)	(SE:1,285)	(SE:1310)	(SE:55)	(SE:7,094)
70 FS	One	162,738 a	21,037 a	20,690 a	4,884 a	209,348 a
		(SE:6,321)	(SE:591)	(SE:1137)	(SE:173)	(SE:8,157)
	Two	184,497 a	16,752 a	17,720 a	3,637 b	222,607 a
		(SE:8322)	(SE:670)	(SE:509)	(SE:181)	(SE:9,662)
CONTROL	One	150,141 a	20,745 a	16,020 a	5,158 a	192,064 a
		(SE:12,607)	(SE:1,868)	(SE:1,681)	(SE:479)	(SE:16,210)
	Two	210,231 b	25,554 a	14,929 a	3,922 b	254,636 b
		(SE:8,922)	(SE:955)	(SE:484)	(SE:143)	(SE:10,370)

Means within the same column in each treatment level indicated by the same letter ‘a’ are not significantly different at $P \leq 0.05$.

The simple effect of site was also studied for partitioning of proportion of biomass components for each treatment separately (Table 8). The mean bole wood proportion was significantly larger while mean foliage proportion was significantly smaller in site two for all treatment levels (50 FS, 70 FS and CONTROL) at α=0.05. Mean branch wood and bark proportions were also smaller in site two; although not significant in all levels of thinning treatments. These results suggest that the stands growing on a relatively better site quality might have allocated more biomass to bole wood and less to foliage.

Table 8. Mean component biomass percentage (proportion×100) by site on different treatment levels.

Treatment	Site	Mean Proportion And Standard Error (S.E.) of Means			
		Bole Wood	**Bark**	**Branch**	**Foliage**
50 FS	One	78.8 a (SE:0.26)	10.2 a (SE:0.21)	8.8 a (SE:0.28)	2.1 a (SE:0.034)
	Two	81.6 b (SE:0.65)	7.4 b (SE:0.39)	9.4 a (SE:0.91)	1.6 b (SE:0.08)
70 FS	One	77.7 a (SE:0.16)	10.1 a (SE:0.16)	9.8 a (SE:0.16)	2.3 a (SE:0.034)
	Two	82.9 b (SE:0.15)	7.5 b (SE:0.05)	7.9 a (SE:0.22)	1.6 b (SE:0.02)
CONTROL	One	78.2 a (SE:0.70)	10.8 a (SE:0.15)	8.3 a (SE:0.45)	2.7 a (SE:0.094)
	Two	82.5 b (SE:0.18)	10 a (SE:0.10)	5.9 b (SE:0.15)	1.5 b (SE:0.018)

Means within the same column in each treatment level indicated by the same letter ‘a’ are not significantly different at $P \leq 0.05$.

3.4. Conclusion and Recommendations

Thinning affects the total biomass in shortleaf pine stands. Removal of biomass stock during the time of thinning can be recovered eventually due to increases in growth efficiency in thinned plots. The results of the present study showed that the thinning to 70 percent of full stocking treatment has already exceeded the bole wood and total biomass contained in its unthinned counterpart on site one in 16 years. However, heavily thinned stands may take much longer to converge. The branch biomass was larger for thinned shortleaf pine stands while stand level foliage and bark biomass decreased with increase of thinning intensity. This reduction in foliage and bark biomass might be due to large reduction of stocking during thinning.

The partitioning of biomass components that was affected by thinning were primarily braches and bark. Unless heavily thinned, thinning treatments did not significantly effect the biomass allocation to bole. Biomass partitioning to branches was larger with the increase of thinning intensity. Although thinning seemed to reduce the total foliage biomass, it was evident that heavily thinned stands increase in terms of proportion of foliage to total biomass. Thinned stands partitioned smaller proportions of total biomass to bark. This in part might be due to the large number of trees in unthinned stand. A large number of small size circles have a large perimeter to area ratio than compared to the smaller number of larger circles, and bark may be roughly proportional to perimeter. A study of the effect of thinning on biomass partitioning at tree-level is needed to further investigate the findings of the present study at stand level. Biomass partitioning was also affected by site quality. The results suggest that the stands growing on relatively better site qualities allocate more biomass to bole wood and less to foliage.

Based on the present study thinning is recommended for a shortleaf pine stand managed for timber production where larger trees are desired. Knowledge of the effects of thinning on bole, bark and foliage biomass can aid foresters in decision making that may relate not only to timber production but also to control burning and fire danger, as well as wildlife and aesthetic concerns.

Literature Cited

Baldwin Jr., V.C., K.D. Peterson, A. Clark III, R.B. Ferguson, M.R. Strub, and D.R. Bower. 2000. The effects of spacing and thinning on stand and tree characteristics of 38-year-old loblolly pine. For. Ecol. Manege. 137:91-102.

Baldwin, V.C., Jr., and D.P. Feduccia. 1987. Loblolly pine growth and yield prediction for managed West Gulf plantations. U.S. For. Serv. Res. Pap. So-236.

Bartelink, H.H. 1998. A model for biomass partitioning in trees. Tree Physiol. 18-91-101.

Blevins, D.P., C.E. Prescott, H. L. Allen, and T. A. Newsome. 2005.The effects of nutrition and density on growth, foliage biomass, and growth efficiency of high-density fire-origin lodgepole pine in central British Columbia. Can. J. For. Res. 35: 2851–2859.

Borders, B.E. 1984. Stand dynamics in plantations of slash and loblolly pine. Ph.D. Dissertation, University of Georgia, Warnell School of Forest Resources, Athens, GA, 250p.

Burkes, E.C., R.E.Will, G.A. Barron-Gafford, R.O. Teskey, B. Shiver. 2003. Biomass partitioning and growth efficiency of intensively managed *Pinus taeda* and *Pinus elliotti* stands of different planting density. For. Sci. 47:224-234.

Daniel T.W., J.A. Helms and F.S. Baker. 1979. Principles of Silviculture, 2nd ed. New York: McGraw-Hill.

Hamilton, G.J. 1976. The Bowmont Norway spruce thinning experiment 1930-1974. Forestry, 49:109-121.

Hasenauer, H., H. E. Burkhart and R.L. Amateis. 1997. Basal area development in thinned and unthinned loblolly pine plantations. For. Sci. 31:731-741.

Kellomäki, S. P. Oker-Blom, E. Valtonen and H. Väisänen. 1989. Structural development of Scots pine stands with varying initial density: effect of pruning on branchiness of wood. For. Ecol. Mange. 27:219-233.

Kramer, P.J. and T.T. Kozlowski. 1960. Physiology of Trees. McGraw-Hill, New York, NY, United States. 641p.

McConnell, B.R. and J.G. Smith. 1970. Response of Understory Vegetation to Ponderosa Pine Thinning in Eastern Washington. Journal of Range Management. 23(3): 208-212

Nebeker, T.E., J.D. Hodges, B.K. Karr and D.M. Moehring. 1985. Thinning practices in southern pines with pest management recommendations. USDA For. Sci. Soc. Am. J. 54:234-237.

Nyland, R.D. 1996. Silviculture: Concepts and Applications. McGraw-Hill Companies Inc., Unites States 633p.

Peterson, J.A., J.R. Seiler, J. Nowak, S.E. Ginn and R.E. Kreh. 1997. Growth and physiological responses of young loblolly pine stands to thinning. For. Sci. 43:529-534.

Phipps, H.M. 1973. Effect of thinning on young shortleaf pine plantations in Indiana. Research Paper NC-93, USDA, FS, NC For. Esp. Stn. 6p.

Rogers, R. 1983. Guides for thinning shortleaf pine. P. 217-225 in Proc. 2nd Bienn. South. Silv. Res. Conf., Jones Jr., E.P. (ed) USDA For. Serv. Gen. Tech. Rep. SE-24. 514p.

Sabatia, C.O. 2007. Effect of thinning on partitioning of aboveground biomass in Naturally Regenerated Shortleaf pine (*Pinus echinata* Mill.). M.S. Thesis. Oklahoma State University, Oklahoma. 75p

SAS Institute Inc. 2002-2004. SAS 9.1.3 Help and Documentation, Cray, NC: SAS Institute Inc.

Society of American Foresters. 1958. Forestry terminology. Society of American Foresters, Washington, D.C. 97p.

Stephen C. S.S. and E. J. Jokela. 1992. Thinning and Fertilizing South Pine Stands of the Lower Coastal Plain: Biological and Economic Effects. South. J. Appl. For. 16:186193.

Suzuki, N. and J.P. Hayes. 2003. Effects of Thinning on Small Mammals in Oregon Coastal Forests. The Journal of Wildlife Management, 67(2): 352-371

Thomas, S.C., C.B. Halpern, D. A. Falk, D.A. Liguori and K. A. Austin. 1999. Plant Diversity in Managed Forests: Understory Responses to Thinning and Fertilization. Ecological Applications. 9(3). 864-879

Wittwer, R. F., T.B. Lynch and M.M. Huebschmann. 1996. Thinning Improves Growth of Crop Tree in Natural Shortleaf Pine Stands. South. J. Appl. For. 20(4):182-187.

Wittwer, R. F., T.B. Lynch and M.M. Huebschmann. 1998. Stand density index for shortleaf pine (*Pinus echinata* Mill.) natural stands. P. 590-596. In Proc 9th Biennial South. Silv. Res. Conf., Waldrop, T.A. (ed). USDA For. Serv. Gen. Tech. Rep. SRS-20.

Appendices

Appendix I: Total tree and tree component biomasses (per hectare basis) in each plot for site One (Johns Valley) and site Two (Cox Ranch).

Site	Block	Plot	Treatment	Bole wood (kg/ha)	Bark (kg/ha)	Total bole (kg/ha)	Branch (kg/ha)	Foliage (kg/ha)	Total Tree (kg/ha)
One	LP	1	30FS	112954	13865	126819	17987	4127	148934
One	LP	2	50FS	140396	17998	158393	14886	3644	176923
One	LP	3	CTRL	160494	21265	181760	15109	5056	201925
One	LP	4	70FS	161209	21404	182613	20631	4995	208238
One	PC	1	70FS	152633	19879	172512	18750	4543	195805
One	PC	2	CTRL	164875	23690	188565	19279	6036	213880
One	PC	3	30FS	111156	15457	126613	19372	4552	150537
One	PC	4	50FS	124322	16785	141106	13838	3420	158364
One	UP	1	50FS	138734	17418	156152	16529	3826	176507
One	UP	2	30FS	98921	12705	111626	20459	4132	136217
One	UP	3	CTRL	125052	17280	142333	13670	4383	160386
One	UP	4	70FS	174371	21827	196199	22688	5113	223999
Two	D	1	50FS	147338	12346	159684	18224	3167	181075
Two	E	1	50FS	170255	16733	186988	15524	3069	205581
Two	W	1	50FS	154547	13881	168428	20033	3259	191720
Two	D	3	70FS	197538	17663	215201	18390	3968	237559
Two	E	2	70FS	169018	15445	184463	16721	3345	204529
Two	W	2	70FS	186936	17149	204085	18049	3599	225733
Two	D	2	CTRL	224079	26710	250789	15899	4188	270876
Two	E	3	CTRL	193560	23657	217217	14429	3696	235342
Two	W	3	CTRL	213053	26294	239347	14460	3884	257691

LP, PC, and UP are blocks in site one; E, W, and D are blocks in site two; 30 FS is thinning to 30 % of full stocking, 50 FS is 50% of full stocking, 70 FS is 70 % of full stocking and CTRL is control unthinned.

Appendix II: Percentage (proportion×100) of tree component biomasses to total tree biomass by site and treatments.

Site	Block	Plot	Treatment	Bole Wood	Bark	Branch	Foliage
One	LP	1	30FS	75.84	9.31	12.08	2.77
One	LP	2	50FS	79.35	10.17	8.41	2.06
One	LP	3	CTRL	79.48	10.53	7.48	2.50
One	LP	4	70FS	77.42	10.28	9.91	2.40
One	PC	1	70FS	77.95	10.15	9.58	2.32
One	PC	2	CTRL	77.09	11.08	9.01	2.82
One	PC	3	30FS	73.84	10.27	12.87	3.02
One	PC	4	50FS	78.50	10.60	8.74	2.16
One	UP	1	50FS	78.60	9.87	9.36	2.17
One	UP	2	30FS	72.62	9.33	15.02	3.03
One	UP	3	CTRL	77.97	10.77	8.52	2.73
One	UP	4	70FS	77.84	9.74	10.13	2.28
Two	D	1	50FS	81.37	6.82	10.06	1.75
Two	E	1	50FS	82.81	8.14	7.55	1.49
Two	W	1	50FS	80.61	7.24	10.45	1.70
Two	D	3	70FS	83.15	7.44	7.44	1.67
Two	E	2	70FS	82.64	7.55	8.18	1.64
Two	W	2	70FS	82.81	7.60	8.00	1.59
Two	D	2	CTRL	82.72	9.86	5.87	1.55
Two	E	3	CTRL	82.17	10.05	6.13	1.57
Two	W	3	CTRL	82.68	10.20	5.61	1.51

LP, PC, and UP are blocks in site one; E, W, and D are blocks in site two; 30 FS is thinning to 30 % of full stocking, 50 FS is 50% of full stocking, 70 FS is 70 % of full stocking and CTRL is control unthinned.

VITA

Nabin Gyawali

Candidate for the Degree of

Master of Science

Thesis: ABOVEGROUND BIOMASS PARTITIONING DUE TO THINNING IN NATURALLY REGENERATED EVEN-AGED SHORTLEAF PINE (*Pinus echinata* Mill.) STANDS IN SOUTHEAST OKLAHOMA

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Title of Study: ABOVEGROUND BIOMASS PARTITIONING DUE TO THINNING IN NATURALLY REGENERATED EVEN-AGED SHORTLEAF PINE (*Pinus echinata* Mill.) STANDS IN SOUTHEAST OKLAHOMA

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Scope of Study:

Tree biomass equations were fitted for shortleaf pine in southeast Oklahoma. Biomass equations developed by nonlinear regression techniques were used to estimate the tree and tree components biomass in unthinned control and thinned stands having three levels of thinning intensity. Biomasses in different thinning treatments were then compared using ANOVA techniques to investigate the response of aboveground biomass partitioning to thinnning.

Finding and Conclusions:

Biomass partitioning was affected by thinning mainly to braches and bark. Unless heavily thinned, thinning treatment did not significantly affect the biomass allocation to bole. Biomass partitioning to branches was found to be higher with the increase of thinning intensity. Although the thinning seemed to reduce the total foliage biomass, it was evident that heavily thinned stands increase their portioning of biomass to foliage. Thinned stands partitioned smaller proportions of total biomass to bark.

ADVISER'S APPROVAL: Thomas B. Lynch